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TECHNICAL NOTE 2127

AN INVESTIGATION OF THE EFFECT OF TETRAETHYL LEAD AND
ETHYL NITRITE ON THE AUTOIGNITION CHARACTERISTICS
OF ISOOCTANE AND TRIPTANE

By J. U. Jovellanos, E. S. Taylor
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Massachusetts Institute of Technology



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SUMMARY

The work described in this report is a continuation of previous work done at the Massachusetts Institute of Technology on the ignition of fuel-air mixtures by means of rapid adiabatic compression.

The purpose of the present investigation was, essentially, to study the effect of tetraethyl lead, a knock inhibitor, on isooctane.

Before making the subject tests, it was supposed that the effect of adding tetraethyl lead would be to change the length of the delay period, at a given fuel-air ratio and compression ratio. These tests showed for compression ratios between 8.0 and 14.9 that varying the concentration of tetraethyl lead in isooctane has a very small effect on the delay at fuel-air ratios between 0.060 and 0.090, whereas, at very rich (0.130 to 0.170) or very lean (0.030 to 0.050) fuel-air ratios, lead appears to have some effect on the ignition delay; the extent of this effect could not be exactly determined because of the difficulty in reproducing results at these extreme fuel-air ratios. The chief difference in the pressure-time curve caused by variation in tetraethyl-lead concentration is to change the "critical explosion pressure," which is defined as the pressure at which a very sudden increase in the rate of pressure rise occurs. The critical explosion pressure, so defined, shows consistent differences which are a function of tetraethyl-lead concentration.

The effect described would appear to indicate that the detonation-inhibiting effect of tetraethyl lead, when used in engine fuels, is due to the fact that it tends to reduce the amount of end gas which reacts with extreme rapidity.

A brief study of the effect of ethyl nitrite, a knock inducer, on triptane was also made. This study showed that, at the chemically correct fuel-air ratio, increasing the concentration of ethyl nitrite in triptane decreases both the delay and the critical explosion pressure.

All tests were carried out in a modified version of the original M.I.T. rapid compression machine. Details of the new machine are presented.

INTRODUCTION

This project is a continuation of work in the field of detonation research conducted at the Massachusetts Institute of Technology under the auspices of and with the financial support of the National Advisory Committee for Aeronautics. Previous work at M.I.T. in this field is covered by references 1 to 4.

The general objective of the work was to study the autoignition of fuel-air mixtures under conditions of rapid compression. The particular objective of the work was to apply the information thus gained to the study of detonation in spark-ignition engines. Since it is believed that detonation in an engine is caused by the rapid compression of the end gas with subsequent autoignition, a study of the pressure-time histories of fuel-air mixtures obtained with the rapid compression machine should yield valuable information regarding the nature of the reactions in the end gas preceding detonation.

The previous work revealed that the general nature of the pressure-time curve was somewhat different for triptane, and very different for benzene, as compared with the nature of the curves for isooctane and 100-octane gasoline. A point of similarity between all four fuels, however, was that the principal effect of varying the fuel-air ratio or compression ratio was to change the delay, that is, the time between completion of the compression stroke and the start of a rapid pressure rise.

Also, the work done to date points to the practicability of using the machine as a tool for determining the probable detonation tendencies of a given fuel under proposed engine conditions. In order to achieve this purpose, a considerable amount of exploratory work on various fuels and test conditions must be carried out and a correlation established between these results and actual engine tests.

It is too early to say what degree of generality may be expected in these correlations, but the present evidence is to the effect that such general correlations do exist.

APPARATUS

The M.I.T. rapid compression machine has been modified to incorporate certain refinements as suggested by experience. The original machine is completely described in reference 2 and will be referred to hereafter as rapid compression machine 1. A cross-sectional view of the original machine is shown in figure 1. It will be noticed that in this apparatus the combustion cylinder (4) is located inside the main cylinder (2), and that the driving piston (5) and the combustion piston (9) form a single unit.

This arrangement had several disadvantages, principal among which was the difficulty of alining the combustion and main cylinders with the high degree of accuracy necessary to achieve gastightness in the unlubricated combustion cylinder.

In the new machine (fig. 2) this difficulty was avoided by locating the combustion cylinder outside the main cylinder. It will also be noticed that a much larger area is provided on the piston skirt for sealing purposes. In the original apparatus it was not possible to take advantage of the entire area of the combustion-piston skirt for this purpose.

It was hoped that these changes would reduce the combustion-chamber leakage to inconsequential proportions, and that the reproducibility of the apparatus would be substantially improved. In these respects, the results of the changes have exceeded expectations.

The basic principle of operation of the old machine has been maintained in the new one. In use, a charge of nitrogen at about 500 pounds per square inch is admitted to the upper cylinder (1) (fig. 2) and confined therein by the poppet valve (2) until ready for release. This valve is drawn tightly against its seat by means of the screw jack (3) acting on the shear pins (4) passed through the valve stem. The poppet valve is suddenly opened by dropping a weight on the end of the valve stem thus shearing the pins and allowing the confined nitrogen to rush into the driving cylinder (5), where it acts on the driving piston (6) causing it to descend rapidly. The driving piston is connected to the combustion piston (7) by means of the rod (8) and thus the explosive mixture, which is placed in the combustion cylinder (9), is rapidly compressed. Photographs of the two pistons and associated parts are shown in figure 3.

In order to prevent damage to the moving parts at the end of the stroke a charge of nitrogen at about 60 pounds per square inch is admitted to the cushion chamber (10), just before releasing the poppet valve. As the driving piston descends, the pressure of this entrapped nitrogen builds up sufficiently to slow the piston down to negligible velocity at the end of the stroke. In this position the ports (11) in the piston register with the ports (12) in the sleeve and the cushion pressure is released, allowing the piston to settle gently without severe impact or rebound.

Both the driving and combustion pistons are prevented from subsequently moving upward by the remaining driving pressure acting downward on the driving piston.

Pressures in the combustion cylinder were recorded by means of a strain gage (13) cemented on the underside of the cylinder head (14) and connected to a camera-oscillograph system. The pressure records so obtained will be explained fully in the section INTERPRETATION OF RECORDS.

The motion of the combustion piston was recorded by photographing the motion of the connecting rod. This was done by painting a series of white horizontal lines $1/4$ inch apart on the surface of the rod and photographing their transits across the field of vision of the camera (15). A vertical slit was placed inside the camera close to the film so that only a small segment of each white line was photographed. The film was moved at a constant known speed at right angles to the motion of the rod with the result that a series of sloping lines was recorded. The position and slope of the lines gave a true indication of the position and velocity of the connecting rod, and thus of the two pistons, at any instant. Specimen records may be seen in figure 4.

A more detailed description of the rapid compression machine 2 will be found in appendix A.

Photographs of the complete apparatus are shown in figure 5 and a schematic diagram showing the component parts rearranged from their actual positions for the sake of clarity is given in figure 6. The auxiliary apparatus is identical with that described in reference 2, except for the replacement of the old drying tower with a new one and the elimination of the humidifier.

The new drying tower consisted of a piece of standard 8-inch pipe, 72 inches long, fitted with heavy flanges on both ends. It was filled with 86 pounds of activated alumina and was connected in the air line between the air pump (56) and the mixing tank (52).

The humidifier was unnecessary in this work because the tests were conducted with dry air only.

TEST PROCEDURE

The experimental work was arranged in four series of tests as follows:

Series 1 - The effect of tetraethyl lead on isooctane at constant fuel-air ratio and compression ratio:

- (1) Tetraethyl-lead concentration varied from 0 to 8 milliliters per gallon
- (2) Fuel-air ratio constant at 0.067 (chemically correct)
- (3) Compression ratio constant at 11.7

Series 2 - The effect of tetraethyl lead on isooctane at various fuel-air ratios:

- (1) Tetraethyl-lead concentration varied from 0 to 4 milliliters per gallon
- (2) Fuel-air ratio varied from 0.030 to 0.170
- (3) Compression ratio constant at 11.7

Series 3 - The effect of tetraethyl lead on isooctane at various compression ratios:

- (1) Tetraethyl-lead concentration varied from 0 to 4 milliliters per gallon
- (2) Compression ratio varied from 8.0 to 14.9
- (3) Fuel-air ratio constant at 0.067 (chemically correct)

Series 4 - The effect of ethyl nitrite on triptane:

- (1) Ethyl-nitrite concentration varied from 0 to 488 milliliters per gallon
- (2) Fuel-air ratio constant at 0.066 (chemically correct)
- (3) Compression ratio constant at 11.7

The variables held constant during all these tests were:

Initial pressure, lb/sq in. abs.	14.7
Initial temperature, °R	609
Compression time, sec	0.006
Dew point of air, °F	-68

The isooctane (2,2,4 trimethylpentane, designated as S-4 reference fuel) was obtained from the Shell Oil Company, Inc., of Wood River, Ill.

The triptane (2,2,3 trimethylbutane) was obtained through the courtesy of the General Motors Corporation, Detroit, Mich.

The tetraethyl lead, designated as "1-T Mix Blue Aviation Ethyl Fluid," was obtained from the Ethyl Corporation of New York. This product consists of tetraethyl lead blended with the theoretical combining concentration of ethylene dibromide and one-half the theoretical combining concentration of ethylene dichloride. One milliliter of Ethyl Fluid contains 0.653 milliliter of tetraethyl lead. Ethyl Fluid, rather than unblended tetraethyl lead, was used because the unblended product is seldom used in automobile and aircraft engines. Whenever the expressions "lead" or "tetraethyl lead" are used in this report it is to be understood that the blended product is referred to.

The ethyl nitrite, containing 10 percent alcohol in solution, was obtained from Merck & Company, Inc., Rahway, N. J.

The explosive mixtures were prepared in the mixing tank ((52), fig. 6). This tank contains a mixing fan and a floating piston which rises as air is admitted from the pump (56). The tank was flushed with clean dry air by allowing the piston to rise and fall three times before preparing a new batch. The air was thoroughly agitated by the fan during this process.

The tank was then filled with air and the fuel injected through a gland in the top of the tank by means of a hypodermic needle. (See reference 2 for details.) The exact fuel quantity was determined by weighing the hypodermic needle and contents on an analytical balance and the required air quantity was obtained by adjusting the air pressure in the tank. The mixture was kept in the tank for 3 minutes at 609° R and agitated continuously by the fan before admitting it to the combustion chamber.

The combustion cylinder was evacuated by means of the hand pump (71) before admitting the fresh mixture, in order to reduce dilution. Half of the contents of the mixing tank was then allowed to pass through the combustion cylinder in order to further reduce dilution. The ratio of mixture passed through the combustion cylinder to mixture retained in the combustion cylinder was about 125 to 1. The combustion cylinder was sealed off at atmospheric pressure after charging. Two tests, under identical initial conditions, were made from each batch as a check on reproducibility.

The mixing tank, combustion cylinder, and connecting pipes were jacketed and maintained at 609° R. This figure was taken as the initial temperature of the mixture.

A constant driving pressure of 500 pounds per square inch gage and a cushion pressure of 60 pounds per square inch gage were used to give a uniform compression time of 0.006 second.

The combustion-cylinder head was removed after each explosion and the surfaces wiped with a clean cloth. The combustion piston was returned to its original position by pushing it up with a hydraulic jack acting through a piece of hard wood shaped to fit the piston head.

INTERPRETATION OF RECORDS

Specimen records of piston displacement against time and cylinder pressure against time taken at a film speed of 200 inches per second are shown in figure 4.

Considering record 177 in this figure, the piston starts to move at A where the two white lines on the piston record begin to slope away from the horizontal. These two lines are streak images of the two horizontal lines on the piston rod which are opposite the camera lens when the rod is stationary.

The lines on the piston rod are $1/4$ inch apart. As the piston gains velocity the lines become steeper, approaching an almost constant slope which persists for the greater part of the stroke. Toward the end of the stroke the slope decreases rapidly, showing the influence of the cushion pressure, and the piston finally comes to rest at B, rather abruptly in this particular instance. The seating of the piston is also recorded on the pressure record by the high-frequency vibrations C accompanying the mechanical impact. It will be noted that the piston then remains tightly seated during the rest of the process. The gentle waving of the white lines on the piston record after B does not represent actual piston motion but rather relative motion between the camera and the piston rod due to swaying of the camera lens after the impact. The compression time AB is about 0.006 second. The line of atmospheric pressure GH was drawn in the pressure record by projecting the horizontal part of the trace preceding the compression.

The pressure record displays a region of high-frequency vibrations D just before the end of the stroke. These vibrations are characteristic of all pressure records taken with rapid compression machine 2. They are probably due to a "chattering" of the combustion piston as it slides over the unlubricated cylinder walls. It does not appear probable that these vibrations are gas vibrations because they were seldom observed on the pressure records taken with rapid compression machine 1 under similar test conditions.

It will be noticed that in the particular pressure record selected here (177, fig. 4) the pressure rises very considerably after the piston has stopped and that the mixture explodes suddenly at E. The time interval CE is defined as the "delay period" and the maximum pressure F assumed by the mixture before exploding is defined as the "critical explosion pressure."

The critical explosion pressure has significance only up to the point where it coincides with the maximum explosion pressure. A situation similar to this may be observed, for instance, in record 159 (fig. 9(1)).

The critical explosion pressure, or some concept closely allied to it, should be of value in giving some idea of the severity of detonation to be expected from a given fuel when used in an engine. A fuel-air mixture having a low critical explosion pressure would be expected to detonate heavily. This may be inferred from a record like 104 (fig. 9(h)), where the charge explodes with great suddenness. A mixture having the characteristics shown in record 159 (fig. 9(1)), on the other hand, would be expected to detonate little, if any, in an engine. Of course, comparisons are complicated by the variations in the length of the delay period exhibited by different mixtures under given conditions. Nevertheless, an important idea is brought out by these examples, namely, that the severity of detonation in an engine depends in all probability not only on the length of the delay period but also on the value of the critical explosion pressure.

Values of critical explosion pressure were obtained from the relation

$$\text{C.E.P.} = \frac{h}{H} \times p$$

where

- | | |
|---|---|
| H | height of trace at end of compression |
| h | height of trace at critical explosion point |
| p | isentropic pressure at end of compression |

Thus it was assumed that the compression was isentropic and that pressures were directly proportional to the recorded heights. The first of these assumptions is valid to within 1 percent and the second is valid for pressures less than 1000 pounds per square inch absolute (see reference 2). However, the greatest errors in measuring critical explosion pressures were undoubtedly due to the difficulty of identifying the critical explosion point.

Values of isentropic pressure and temperature for the compression ratios used in this work are given in the following table. These values are based on an initial pressure of 14.7 pounds per square inch absolute and 609° R.

Compression ratio	Isentropic compression pressure (lb/sq in. abs.)	Isentropic compression temperature (°R)
8.0	231	1190
8.5	245	1205
8.9	265	1235
9.4	285	1250
10.0	309	1275
10.7	331	1305
11.5	370	1335
11.7	379	1340
12.4	408	1365
13.5	457	1400
14.9	518	1440

DISCUSSION OF RESULTS

Series 1 Tests

The series 1 tests were made to determine the effect of tetraethyl lead on the pressure-time characteristics of isooctane. The only quantity varied was the lead concentration. The records are shown in figure 7.

It will be observed that in the case of unleaded isooctane (records 81, 82, and 120, fig. 7(a)), the delay period ends in a small "fillet" at the end of which the explosion occurs with great suddenness. The point at which the film trace disappears, because of extreme high velocity of the light spot, identifies the critical explosion pressure. As the concentration of lead is increased, the delay period remains essentially unchanged, but the critical explosion pressure increases. At the greatest lead concentration used, 8 milliliters per gallon, the critical explosion pressure approaches the maximum pressure of the explosion (records 129 and 130, fig. 7(f)).

These trends are shown graphically in figure 8 and numerical values, taken from the records, are given in table 1.

Series 2 Tests

In the series 2 tests, two quantities were varied - the lead concentration and the fuel-air ratio. The object was to ascertain whether lead affected the explosion characteristics of isooctane more at one fuel-air ratio than another. Three lead concentrations were used at each fuel-air ratio, namely 0, 2, and 4 milliliters per gallon.

The explosion records are shown in figure 9; measurements of corresponding delays and critical explosion pressures are given in table 2. Curves of delay and critical explosion pressure against fuel-air ratio for each lead concentration are given in figures 10 to 12, and the results are summarized in figures 13 and 14.

The records of figure 9(a) show that at a fuel-air ratio of 0.030 the critical explosion pressure is none too well defined. Nevertheless, it is quite apparent that it increases with lead additions. The delay at this same fuel-air ratio appears to go through a minimum at a lead concentration of 2 milliliters per gallon. The same trends may be noted for a fuel-air ratio of 0.040 in figure 9(b).

The critical explosion pressure is more easily identified as the fuel-air ratio is increased (see figs. 9(c) to 9(j)), but beyond 0.130 it again becomes difficult to recognize (see figs. 9(k) to 9(n)) and the concept loses all real significance. Therefore, no attempt was made to measure critical explosion pressures beyond a fuel-air ratio of 0.130.

The delay for some of the records in figures 9(l) to 9(n) was so long that a section was removed from the records to facilitate publication. The actual duration of the delay is noted on such records.

The trends in delay and critical explosion pressure for this series of tests may be more easily recognized by noting the curves of figures 13 and 14. It will be observed in figure 13 that the delay is not greatly affected by lead additions at fuel-air ratios between 0.060 and 0.090. In the rich range a minimum value of delay appears to exist at a lead concentration of 2 milliliters per gallon for a given fuel-air ratio. However, it must be emphasized that reproducibility in the rich range is on the whole rather poor (note scatter of points in figs. 10, 11, and 12) and the relative variations shown in figure 13 must not be interpreted too rigorously.

One broad generalization, however, can be immediately drawn from figure 13, namely, that lead does not greatly affect the general shape of the curve of delay against fuel-air ratio.

The curves of figure 14 show that increasing the concentration of lead always gives a higher critical explosion pressure regardless of the fuel-air ratio and the effect seems to be most pronounced in the rich range.

Series 3 Tests

In the series 3 tests the quantities varied were lead concentration and compression ratio. The object was to determine whether lead affected the explosion characteristics of isooctane more at one compression ratio than another. At each compression ratio lead concentrations of 0, 2, and 4 milliliters per gallon were used.

The explosion records are shown in figure 15; curves of delay and critical explosion pressure against compression ratio for each lead concentration are given in figures 16 to 18. The over-all comparisons of the effect of lead on delay and critical explosion pressure against compression ratio are presented in figures 19 and 20. Measured values of delay and critical explosion taken from the records are given in table 3.

The records of figure 15(a) show that at a compression ratio of 8.0, the delays are long and the critical explosion pressures poorly defined. The reproducibility is also poor in these records (note the scatter of the experimental points at a compression ratio of 8.0 when plotted in figs. 16, 17, and 18). In spite of these defects a very definite increase in critical explosion pressure with lead concentrations may be noticed in the records of figure 15(a). But no such trend can be noticed in the case of delay because the variations are erratic. The curves of figure 19 show an increase in delay at a compression ratio of 8.0 for a lead concentration of 4 milliliters per gallon, but it is doubtful if these curves can be interpreted so closely in view of the scatter of the points of figures 16, 17, and 18 at a compression ratio of 8.0. At higher values of the compression ratio the reproducibility is generally improved and the curves of figures 16, 17, and 18 leave no doubt as to trends.

It can be generally inferred from these figures that, for any lead concentration up to 4 milliliters per gallon,

(1) Increasing the compression ratio decreases the delay period

(2) The critical explosion pressure first decreases with increasing compression ratio and then increases, the minimum value occurring at a compression ratio between 9 and 9.5

The superimposed curves of delay against compression ratio of figure 19 indicate a small increase in delay with increase in lead concentration in the lower range of compression ratio. However, this increase is too close to the limits of reproducibility to have any real significance.

The superimposed curves of critical explosion pressure against compression ratio in figure 20 indicate that lead additions increase the critical explosion pressure at all compression ratios. The magnitude of this effect leaves no room for doubt except perhaps in the region of a compression ratio of 8.0 where the reproducibility is poor.

Series 4 Tests

The influence of a detonation inducer, ethyl nitrite, on the explosion characteristics of triptane was examined in the series 4 tests. Triptane was selected as a fuel because it has an inherently high critical explosion pressure. It was inferred that ethyl nitrite, because of its contrary behavior to tetraethyl lead in an engine as regards detonation would tend to lower the critical explosion pressure. This reasoning proved to be correct.

The explosion records are shown in figure 21. Curves of delay and critical explosion pressure against ethyl-nitrite concentration are given in figure 22 and measured data from the records are presented in table 4.

The compression ratio was maintained at 11.7 and the chemically correct fuel-air ratio, 0.066, was used throughout these tests, the only variable being the concentration of ethyl nitrite.

A study of the records of figure 21 indicates that there is a very definite decrease in both the critical explosion pressure and the delay with increase in ethyl-nitrite concentration. This can be easily seen in figure 22. The first 8 milliliters of ethyl nitrite reduce the critical explosion pressure very considerably while affecting the delay period only to a negligible extent. At much heavier concentrations both the critical explosion pressure and the delay period are diminished. The rate of decrease appears constant and roughly the same in either case.

At the heaviest concentration of ethyl nitrite used, 488 milliliters per gallon, the explosion records (344, 345, and 346, fig. 21(f)) look very much like those of unleaded isooctane (see records 81, 82, and 120, fig. 7(a)).

Thus, by adding sufficient ethyl nitrite to triptane it can be made to assume the explosion characteristics of unleaded isooctane and, conversely, by adding sufficient tetraethyl lead to isooctane an explosion record resembling pure triptane can be obtained.

RELATION OF RESULTS TO DETONATION IN ENGINES

Judging from the foregoing results, it seems probable that the action of tetraethyl lead in reducing the tendency to detonate in engines is not due to a change in the time (crank angle) required for rapid end-gas reaction to develop. The effect appears to be rather one of altering the later stages of end-gas reaction so as to reduce the quantity of end gas which reacts with sufficient rapidity to set up intense pressure waves in the charge.

The effect of changing from isooctane to benzene, reported in reference 1, was somewhat similar to the effect of increasing the lead concentration in isooctane reported in the present investigation, in that the rapidity of reaction was reduced, with no significant change in the time to complete the reaction.

On the other hand, reference 1 indicated that, for all the fuels tested, a change in fuel-air ratio causes changes in the time required to complete the reaction. In each case the fuel-air ratio for minimum time of reaction corresponds quite closely to the fuel-air ratio for maximum detonation in an engine.

REPRODUCIBILITY OF RESULTS

General Reproducibility

A general impression of the reproducibility of rapid compression machine 2 can be had by noting the scatter of the points in figures 8, 10, 11, 12, 16, 17, 18, and 22.

Evidently there is still room for improvement. However, by comparison with rapid compression machine 1, it will be observed that appreciable gains have been made. In figure 23 curves of ignition delay against fuel-air ratio and ignition delay against compression ratio (taken from figs. 35 and 39 of reference 1) representing data taken with rapid compression machine 1 are compared with similar curves (from figs. 10 and 16 of the present report) taken with rapid compression machine 2. The fuel is isooctane and initial conditions are the same in either case.

Sample records taken with the two machines under identical conditions are shown for comparison purposes in figure 24. Measured values from these records are given in table 5. These data indicate an overall improvement in reproducibility for rapid compression machine 2.

It would be difficult to try to give an exact figure to represent the reproducibility of either rapid compression machine, or to measure the superiority of rapid compression machine 2 over rapid compression machine 1 in this respect. Reproducibility may be gaged on the basis of ignition delay, critical explosion pressure, compression pressure, and so forth and experience so far indicates that good reproducibility according to one standard does not necessarily mean good reproducibility according to another. For instance, in figure 10, the reproducibility at a fuel-air ratio of 0.095 is excellent when delay is used as a criterion and rather poor when critical explosion pressure is used.

The ideal, of course, is realized when two records taken under identical conditions coincide exactly throughout their entire length when superimposed. Any divergence from this condition would be a measure of the reproducibility - but the difficulty is in determining at what point to measure the divergence.

Effect of Combustion-Chamber Leakage

The gastightness of the combustion chamber was tested by filling the chamber with nitrogen at 800 pounds per square inch and timing the rate of drop in pressure. A special combustion cylinder head was used for this purpose having a hole in the center by means of which the necessary fittings could be attached.

Curves of combustion-chamber pressure against time measured from an initial pressure of 800 pounds per square inch are given in figure 25. These curves show that, with rapid compression machine 2, after 60 runs the lead seal had improved to the extent shown by the top curve in the figure and after 300 runs (at the conclusion of the work) the seal was still in excellent condition.

When it is taken into consideration that the events studied with this machine occupy at most only a few hundredths of a second, it will be appreciated that the leakage occurring during this interval should have but a negligible effect on the results.

A leakage curve for rapid compression machine 1 after 50 runs is shown also in figure 25. The decided improvement realized in the new apparatus is apparent. Also, the piston in rapid compression machine 1

had to be re-leadplated after about 80 runs whereas in the new apparatus at least 300 runs can be made before re-leadplating is necessary.

Further details of the leakage test procedure will be found in reference 2.

CONCLUSIONS

The following conclusions resulted from a study, made by means of rapid adiabatic compression, of the effect of tetraethyl lead and ethyl nitrite on the autoignition characteristics of isooctane and triptane:

1. The addition of lead to isooctane raises the critical explosion pressure, thus reducing the fraction of the charge which reacts with extreme rapidity. This observation was found to hold for all compression ratios (8.0 to 14.9) and all fuel-air ratios (0.030 to 0.170) investigated.

2. At fuel-air ratios normally encountered in engine work (0.06 to 0.09), tetraethyl lead has no significant effect on the ignition delay of isooctane.

3. At fuel-air ratio 0.066 and compression ratio 11.7:

(a) Ethyl nitrite reduces the critical explosion pressure of triptane, an effect opposite to that of lead on isooctane. This effect is most pronounced at concentrations of ethyl nitrite below 8 milliliters per gallon although the trend continues at a slow but uniform rate up to concentrations as high as 488 milliliters per gallon.

(b) Ethyl nitrite decreases the delay period of triptane uniformly throughout a range of concentrations from 0 to 488 milliliters per gallon.

Sloan Laboratories for Aircraft and Automotive Engines
Massachusetts Institute of Technology
Cambridge, Mass., May 6, 1947

APPENDIX A

DETAILED DESCRIPTION OF RAPID COMPRESSION MACHINE 2

A sectional drawing of M.I.T. rapid compression machine 2 is shown in figure 2. The machine consists essentially of the upper cylinder (1), the driving cylinder (5), the driving piston (6), the connecting rod (8), the combustion cylinder (9), the combustion piston (7), and the poppet valve (2). The whole machine is hung from the supporting table (16) by means of the bolts (17). The upper cylinder, driving cylinder, and poppet valve were taken from the original rapid compression machine 1.

The new driving piston was machined from a billet of 17S-T aluminum alloy. The head of the driving piston was made conical and the underside was carefully machined to fit the conical face of the mild-steel impact block (19). Thus, at the end of the stroke, the driving piston contacted the stationary parts of the apparatus at the lower rim of the skirt, at the lower end of the central boss, and at the conical face of the impact block. The seating area of the driving piston on impact was thus much greater than in the original apparatus and the localized shock loads were correspondingly reduced.

Four radial holes (20) were drilled in the impact block to allow for the escape of nitrogen from the inner region. The block was centered on a shoulder (21) on the cylinder head.

The skirt of the new driving piston was made longer in order to provide better sealing of nitrogen in the cushion chamber when the piston was at the upper end of the stroke. In the old apparatus the skirt was not long enough to prevent excessive leakage of nitrogen through the ports (12) while adjusting the cushion pressure.

The lower cylinder head (22) of the driving cylinder was machined from hot-rolled steel. A small well was provided in the center to receive a seal for the connecting rod. This seal was simply a bearing oil seal of conventional type. It was held in place by a screw plug (24) which tightened against a beveled seat thereby preventing leakage past the threads on the plug.

The connecting rod was made of alloy steel heat-treated to 355 Brinell hardness. Spherical bearings (26) were inserted at the upper end of the connecting rod where it was affixed to the driving piston boss and at the opposite end of the rod in the combustion piston (7). This arrangement took care of any misalignment between the

driving and combustion cylinders. The spherical bearings (26) at the upper end were adapted from ball thrust bearings and those at the lower end were machined especially for the purpose.

The upper end of the connecting rod was secured to the driving piston by the retaining nut (27) which was split at its threaded end and provided with a locking wedge (29) which was drawn tight by means of the Allen screw (30).

The lower spherical bearings consisted of a ball nut (31) of alloy steel having a hardness of 185 Brinell, a spherical socket (32) of the same material, an aluminum-alloy spacer (35) machined spherical at the top, and an aluminum-alloy retaining nut (34) machined to receive the spherical surface of the spacer and by means of which the connecting rod was attached to the combustion piston.

The combustion piston was made from alloy steel heat-treated to 355 Brinell and was ground 0.006 inch smaller than the sleeve. Fourteen circumferential labyrinth grooves 0.125 inch wide and 0.003 inch deep were cut in the skirt and the surface copperplated to a thickness of about 0.0025 inch. The surface was then leadplated (electrolytically) to a thickness of about 0.001 inch and the lead which was deposited in the grooves was removed. The piston was then forced into the combustion cylinder, the excess lead either being sheared off or flowing into the labyrinth grooves. In this manner a very satisfactory sealing was accomplished (see fig. 25 for leakage data) and a certain amount of lubrication was provided by the lead.

The cast-iron combustion cylinder (9) was bolted on to the driving cylinder head. It was provided with a hardened-steel sleeve (37), "aged" by "deep freezing," and then shrunk into the cylinder. The inside surface of the sleeve was ground and lapped. A piece of steel tubing was shrunk on the outside of the cylinder to form a water jacket (38).

The fuel-air mixture was circulated through the combustion cylinder by means of the ports (39) which were made oblique to avoid short-circuiting of the combustion chamber.

The combustion cylinder head (14) was taken from the original machine. It was clamped in place by the cylinder plug (40) and the plate (41). The plate was caused to bear on the plug and the cylinder head by means of four bolts (42) threaded into the lower end of the cylinder. This arrangement prevented any tendency toward twisting of the cylinder head while clamping, a situation which may have existed in the original machine where the plug was screwed in (see (18), fig. 1). This twisting may have been responsible for the inconsistency of pressure calibrations noted in rapid compression machine 1.

As in the original machine, the compression ratio was varied by using impact rings (43) of different thicknesses.

The piston-motion camera (15) was mounted as shown in figure 2. The camera was trained on the connecting rod between the two pistons rather than on the skirt of the driving piston as in rapid compression machine 1. This new arrangement enabled the camera lens to be moved out of the path of the high-pressure gases released from the ports at the end of the stroke. In this way vibrations set up in the camera at the end of the stroke were reduced.

Fourteen horizontal grooves spaced $1/4$ inch apart were cut in the connecting rod along the side facing the camera. These grooves were filled with white enamel and the background surfaces were painted black. The lines were illuminated from a 108-watt spotlight mounted on a rubber vibration isolater. The light beam was focused on the piston rod in such a manner that only two of the white lines were illuminated at a time.

The specifications for rapid compression machine 2 are as follows:

Diameter of driving piston, in.	6.382
Length of driving piston, in.	4.413
Material of driving piston	17S-T aluminum alloy
Diameter of combustion piston, in.	2.00
Length of combustion piston, in.	3.00
Material of combustion piston	chrome-molybdenum steel, 355 Brinell hardness
Stroke, in.	3.000
Range of compression ratio	8.0 to 14.9
Weight of moving parts, lb	8.0

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1. Leary, W. A., Taylor, E. S., Taylor, C. F., and Jovellanos, J. U.: The Effect of Fuel Composition, Compression Pressure, and Fuel-Air Ratio on the Compression-Ignition Characteristics of Several Fuels. NACA TN 1470, 1948.
2. Leary, W. A., Taylor, E. S., Taylor, C. F., and Jovellanos, J. U.: A Rapid Compression Machine Suitable for Studying Short Ignition Delays. NACA TN 1332, 1948.
3. Taylor, E. S., Leary, W. A., and Diver, J. R.: Effect of Fuel-Air Ratio, Inlet Temperature, and Exhaust Pressure on Detonation. NACA Rep. 699, 1939.
4. Leary, W. A., and Taylor, E. S.: The Significance of the Time Concept in Engine Detonation. NACA ARR, Jan. 1943.
5. Welles, O. W.: Theoretical and Actual Dynamics of the M.I.T. Rapid Compression Machine. B. S. and M. S. Thesis, M.I.T., 1943.

TABLE 1

SERIES 1 TESTS - DATA ON EXPLOSION RECORDS FOR ISOOCTANE AT
VARIOUS CONCENTRATIONS OF TETRAETHYL LEAD

[Fuel-air ratio, 0.067 (chemically correct); compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 lb/sq in. abs.; compression pressure, 379 lb/sq in. abs.; compression time, 0.006 sec; film speed, 200 in./sec]

Lead concen- tration (ml/gal)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)
0	81	0.0056	885
	82	.0056	985
	120	.0060	875
.5	121	.0061	875
	122	.0050	875
1.0	123	.0049	1070
	124	.0053	935
2.0	125	.0052	1080
	126	.0060	1105
	132	.0062	1050
4.0	128	.0047	1170
	174	.0059	1072
8.0	129	.0061	1310
	130	.0063	1300

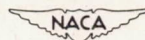


TABLE 2

SERIES 2 TESTS - DATA ON EXPLOSION RECORDS FOR ISOOCTANE AT VARIOUS CONCENTRATIONS

OF TETRAETHYL LEAD AND AT VARIOUS FUEL-AIR RATIOS

[compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 lb/sq in. abs.; compression pressure, 379 lb/sq in. abs.; compression time, 0.006 sec; film speed, 200 in./sec]

Fuel-air ratio	Lead concentration (ml/gal)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)	Fuel-air ratio	Lead concentration (ml/gal)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)
0.030	0	91	0.0180	^a 730	0.110	0	103	0.0102	520
		94	.0232	^a 1135			104	.0077	445
	2.0	143	.0152	^a 1060		2.0	149	.0084	730
		144	.0163	^a 1020			150	.0077	695
	4.0	181	.0175	^a 900		4.0	187	.0098	965
		182	.0186	^a 920			188	.0097	820
.040	0	89	.0114	860	.120	0	105	.0110	600
		90	.0107	640			106	.0095	485
	2.0	137	.0073	1072		2.0	151	.0133	535
		138	.0093	1010			152	.0120	580
	4.0	180	.0117	1140		4.0	190	.0099	595
.050	0	85	.0055	815	.130	0	107	.0117	435
		86	.0061	845			108	.0120	535
	2.0	136	.0055	905		2.0	156	.0121	650
							167	.0137	920
	4.0	177	.0064	1030		4.0	191	.0171	995
		178	.0085	950					
.060	0	83	.0058	895	.140	0	109	.0137	515
							110	.0124	600
	2.0	133	.0054	925		2.0	117	.0229	^a 1690
		134	.0054	985			118	.0207	^a 1895
	4.0	175	.0059	1140		4.0	157	.0189	^a 895
							158	.0143	^a 700
.067	0	81	.0056	885	.150	0	111	.0185	
		82	.0056	985			112	.0243	
	2.0	120	.0060	875		2.0	159	.0245	
							160	.0223	
	4.0	125	.0052	1080		4.0	195	.0334	
		126	.0060	1105					
.078	0	95	.0059	610	.160	0	113	.0460	
		98	.0049	630			114	.0435	
	2.0	145	.0062	810		2.0	162	.0353	
		146	.0063	835			166	.0344	
	4.0	183	.0057	960		4.0	198	.0430	
		184	.0054	1050					
.095	0	101	.0072	640	.170	0	115	(b)	
		102	.0071	730			116	.0460	
	2.0	148	.0060	730		2.0	163	.0565	
		169	.0075	650			164	.0425	
	4.0	170	.0068	590		4.0	199	.0678	
		185	.0075	920			200	.1120	
		186	.0081	990					

^aApproximate.
^bNo explosion.

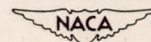


TABLE 3

SERIES 3 TESTS - DATA ON EXPLOSION RECORDS FOR ISOOCTANE AT VARIOUS CONCENTRATIONS

OF TETRAETHYL LEAD AND AT VARIOUS COMPRESSION RATIOS

[Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R;
initial pressure, 14.7 lb/sq in. abs.; compression time, 0.006 sec;
film speed, 200 in./sec]

Compression ratio	Compression pressure (lb/sq in. abs.)	Compression temperature (°R)	Lead concentration (ml/gal)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)
8.0	231	1190	0	319	0.0328	^a 1050
				320	.0232	^a 990
				321	.0325	^a 875
				322	.0242	^a 925
			2.0	264	.0283	^a 1020
				315	.0325	^a 1210
				316	.0288	^a 1315
			4.0	311	.0455	^a 1050
				312	.0344	^a 1150
				313	.0450	990
				314	.0272	1350
8.5	245	1205	0	317	.0203	735
				318	.0164	735
			2.0	261	.0235	1225
				262	.0218	1285
			4.0	308	.0185	1000
				309	.0195	1175
				310	.0182	1140
8.9	265	1235	0	219	.0115	585
				220	.0117	665
				229	.0134	490
				230	.0135	490
			2.0	260	.0165	740
				269	.0143	810
			4.0	285	.0160	885
				286	.0166	735
				306	.0165	770
9.4	285	1250	0	217	.0106	595
				218	.0108	690
			2.0	257	.0122	650
				258	.0113	825
			4.0	284	.0130	855
				294	.0120	850
10.0	309	1275	0	215	.0076	705
				216	.0083	670
			2.0	255	.0105	745
				256	.0082	760
			4.0	281	.0107	985
				282	.0081	905

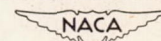
^aApproximate.

TABLE 3

SERIES 3 TESTS - DATA ON EXPLOSION RECORDS FOR ISOOCTANE AT VARIOUS CONCENTRATIONS

OF TETRAETHYL LEAD AND AT VARIOUS COMPRESSION RATIOS - Concluded

[Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R;
 initial pressure, 14.7 lb/sq in. abs.; compression time, 0.006 sec;
 film speed, 200 in./sec]

Compression ratio	Compression pressure (lb/sq in. abs.)	Compression temperature (°R)	Lead concentration (ml/gal)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)
10.7	331	1305	0	213	0.0080	825
				214	.0063	760
			2.0	253	.0076	755
				254	.0075	815
			4.0	280	.0080	990
				292	.0073	865
11.5	370	1335	0	211	.0054	935
				212	.0062	795
			2.0	265	.0053	960
				268	.0063	830
			4.0	277	.0053	1135
				278	.0064	975
12.4	408	1365	0	210	.0048	815
				243	.0045	815
				244	.0043	815
			2.0	249	.0049	1040
				267	.0043	915
			4.0	275	.0052	985
13.5	457	1400	0	208	.0044	915
				237	.0038	915
			2.0	247	.0037	1130
				248	.0049	1190
			4.0	273	.0048	1160
				291	.0031	1330
14.9	518	1440	0	204	.0038	1040
				235	.0035	1040
				236	.0029	990
			2.0	245	.0030	1190
				246	.0034	1225
			4.0	271	.0032	1670
				272	.0030	1475

TABLE 4

SERIES 4 TESTS - DATA ON EXPLOSION RECORDS FOR TRIPTANE AT
VARIOUS CONCENTRATIONS OF ETHYL NITRITE

[Fuel-air ratio, 0.066 (chemically correct); compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 lb/sq in. abs.; compression pressure, 379 lb/sq in. abs.; compression time, 0.006 sec; film speed, 200 in./sec]

Ethyl-nitrite concentration (ml/gal)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)
0	329	0.0064	1600
	330	.0049	1490
	332	.0066	1490
4.0	333	.0056	1160
	334	.0061	1200
8.0	335	.0057	1075
	336	.0070	1065
	337	.0063	1090
120.0	340	.0040	1010
	341	.0041	1030
	347	.0039	950
	348	.0048	920
304.0	351	.0033	815
	352	.0024	785
	354	.0036	760
	356	.0037	680
488.0	344	.0019	520
	345	.0018	495
	346	.0019	560

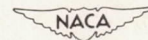


TABLE 5

COMPARISON OF REPRODUCIBILITY OF RAPID COMPRESSION MACHINES 1 AND 2

[Data measured from explosion records of fig. 24. Fuel-air ratio, 0.067; compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 lb/sq in. abs.; compression pressure, 379 lb/sq in. abs.; compression time, 0.006 sec (approx.); film speed, 200 in./sec; fuel, isooctane]

Rapid compression machine 1			Rapid compression machine 2		
Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)	Run	Delay (sec)	Critical explosion pressure (lb/sq in. abs.)
57	0.0055	885	76	0.0056	710
60	.0056	965	77	.0049	860
61	.0055	860	78	.0056	760
62	.0051	1035	79	.0050	760
63	.0071	730	80	.0053	735
64	.0080	730			
	Av. .0059	Av. 870		Av. .0053	Av. 760
	Max. spread .0029	Max. spread 305		Max. spread .0007	Max. spread 150

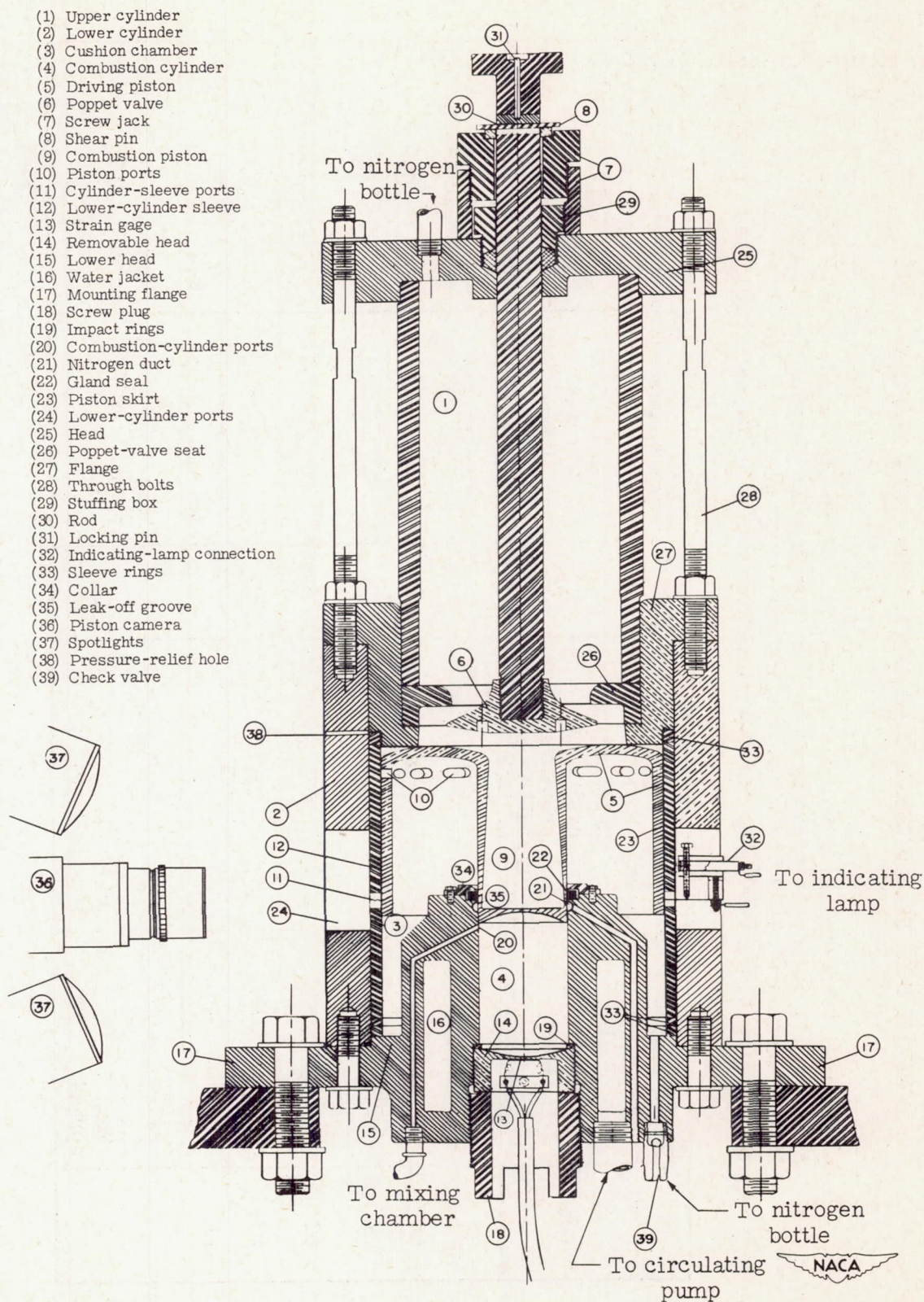


Figure 1.- Sectional view of M.I.T. rapid compression machine 1.

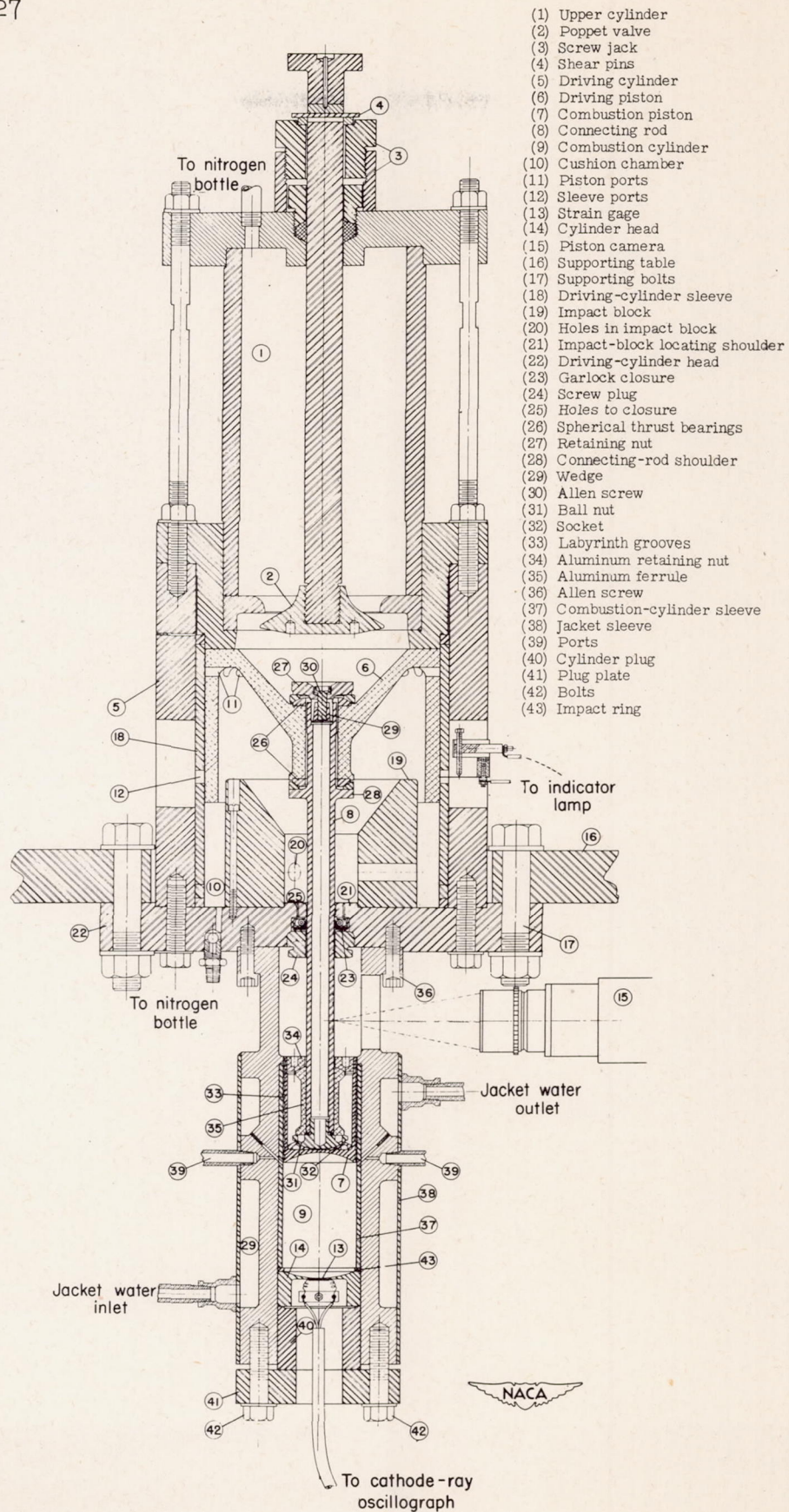


Figure 2.- Sectional view of M.I.T. rapid compression machine 2.

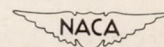
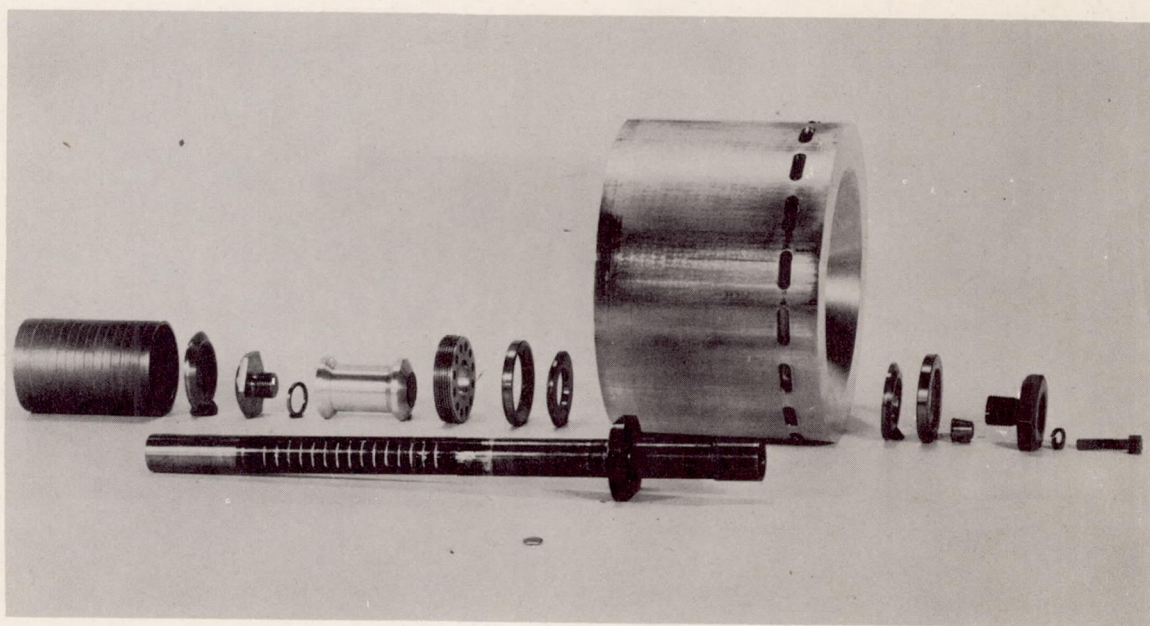
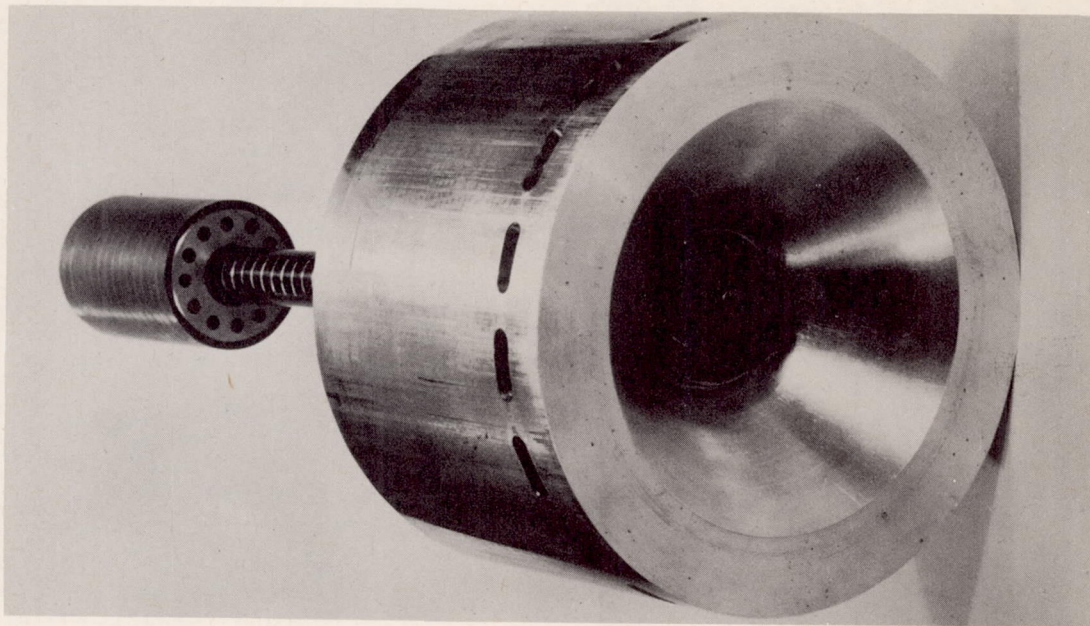


Figure 3.- Driving- and combustion-piston assembly of M.I.T. rapid compression machine 2.

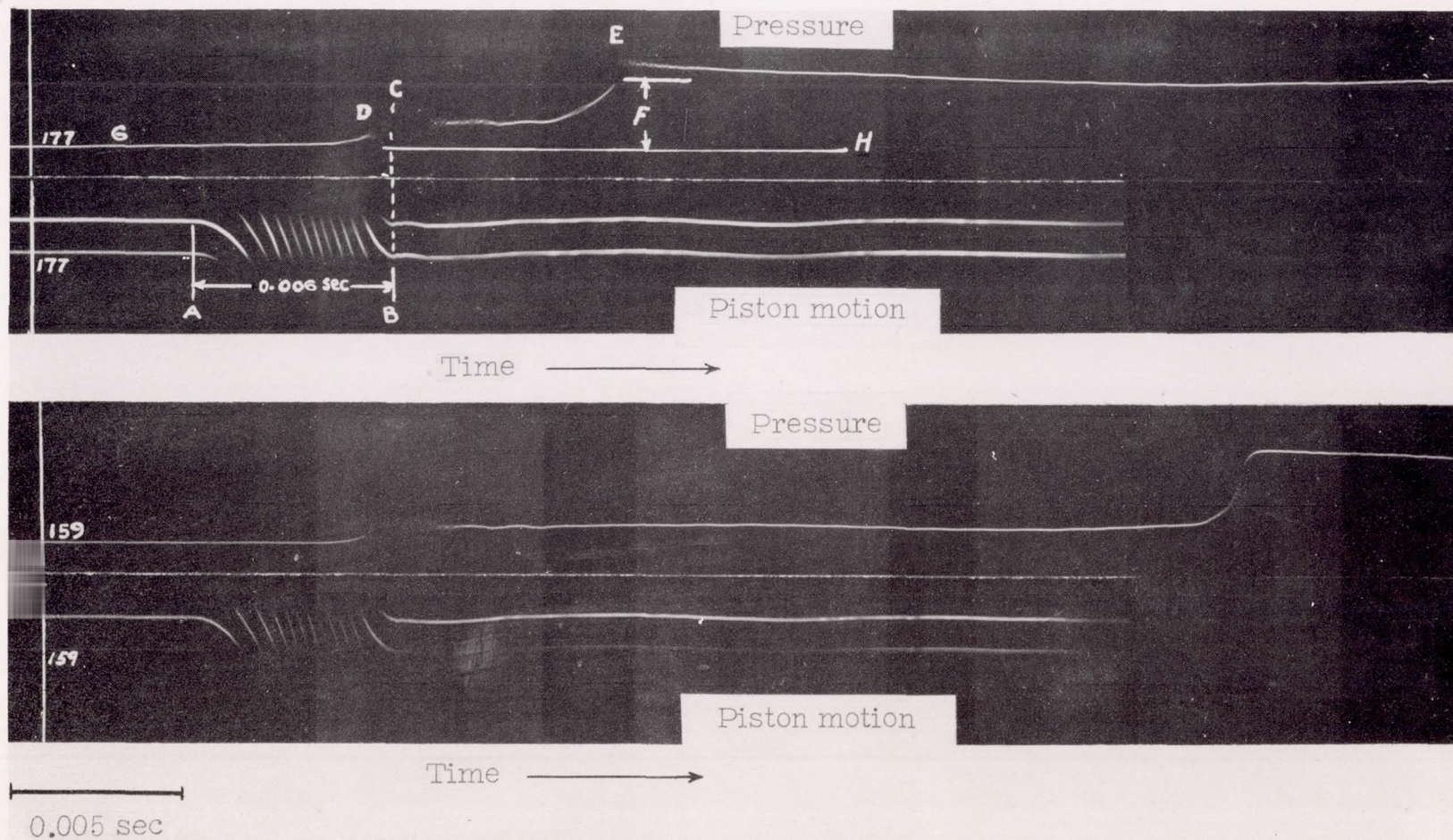
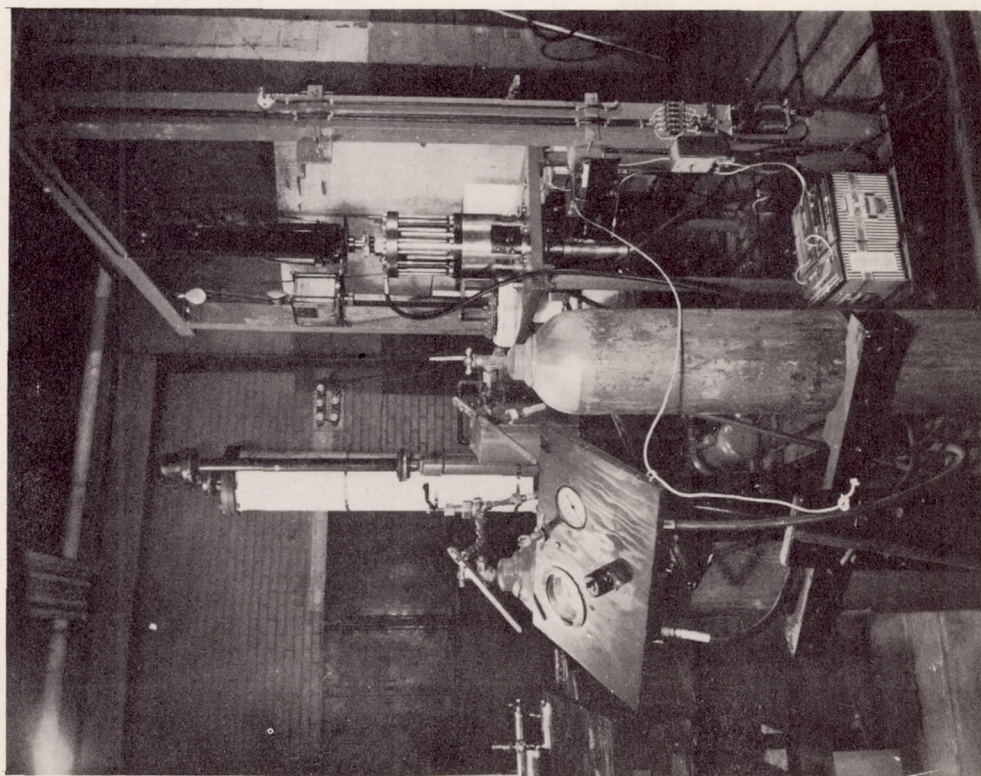
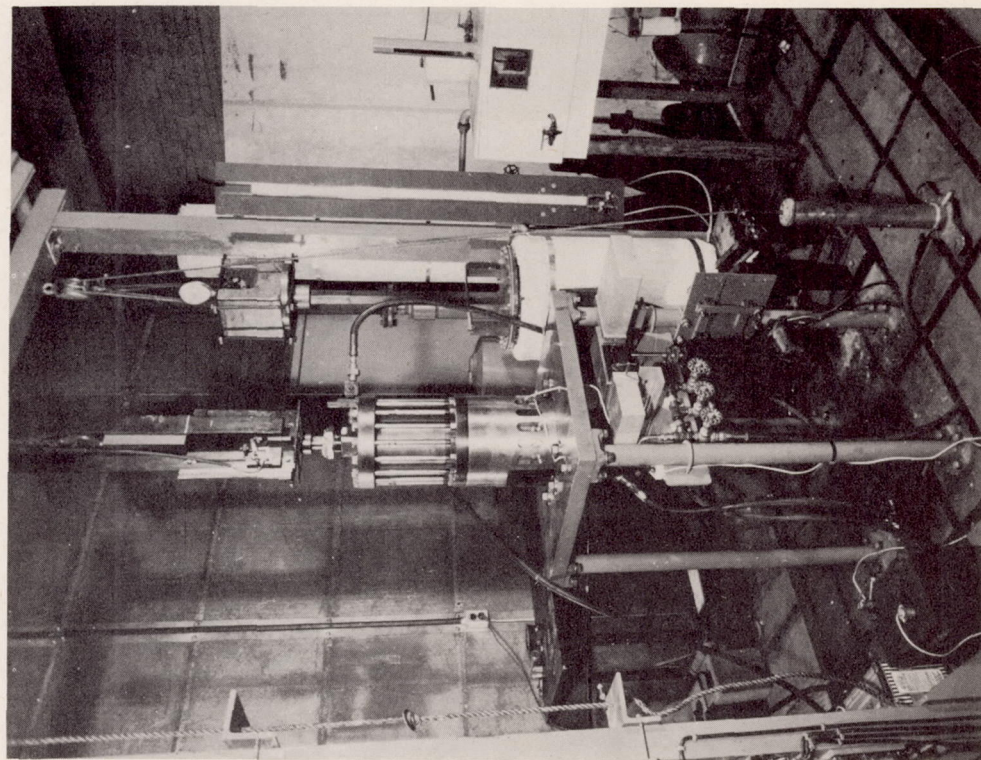


Figure 4.- Specimen records obtained with the M.I.T. rapid compression machine 2. Film speed, 200 inches per second.





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Figure 5.- Photographs of the M.I.T. rapid compression apparatus.

- (44) Rapid compression machine 2
- (45) Drop weight
- (46) Nitrogen cylinder
- (47) Driving-pressure gage
- (48) Cushioning-pressure gage
- (49) Jacket water header tank
- (50) Resistance heating units
- (51) Thermostat
- (52) Fuel-air mixing tank
- (53) Circulating water pump
- (54) Jacket water thermometer
- (55) Heat exchanger
- (56) Air pump
- (57) Drying tower
- (58) Pressure-relief valve

- (59) Air filter
- (60) Dew-point apparatus
- (61) Oscillograph camera
- (62) Cathode-ray oscillograph
- (63) Solenoid
- (64) Oscillograph-camera switch
- (65) Reference-timer switch
- (66) Piston-camera switch
- (67) Pressure-calibration switch
- (68) Piston camera
- (69) Spotlight
- (70) False-start indicating lamp
- (71) Hand vacuum pump
- (72) Mercury manometer
- (73) Mixing-tank safety plug

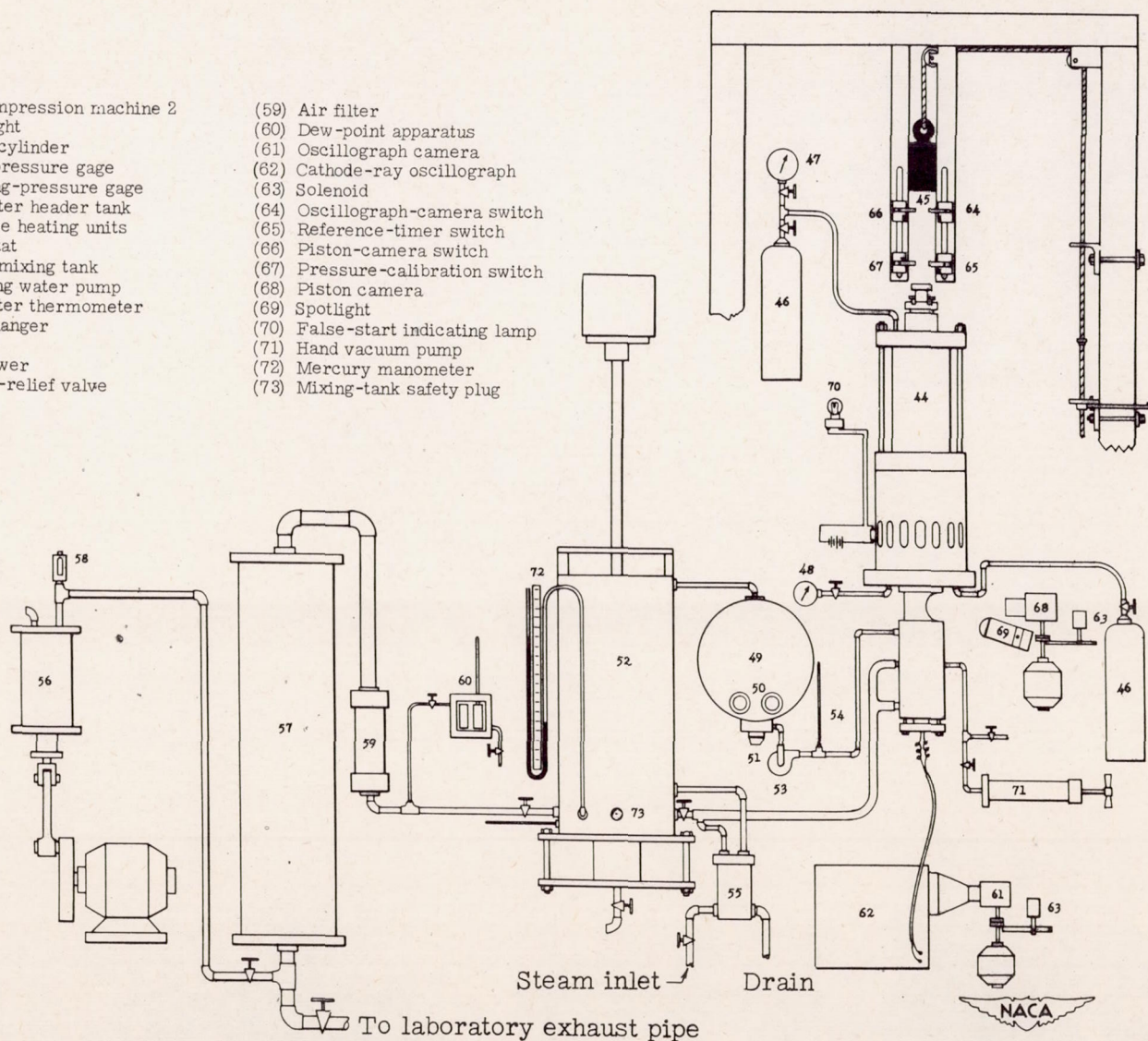
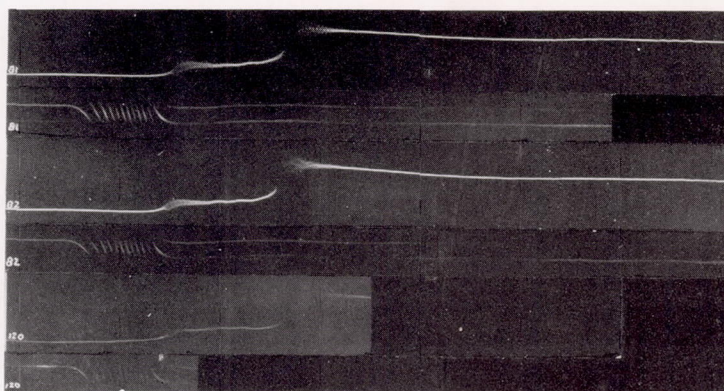
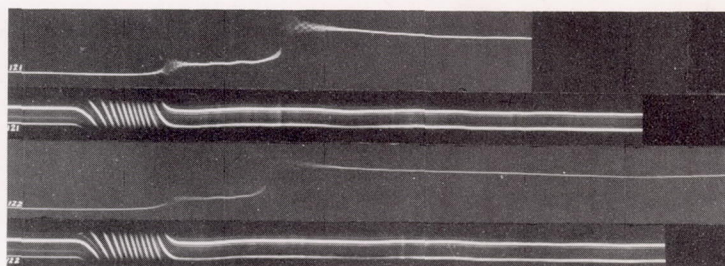


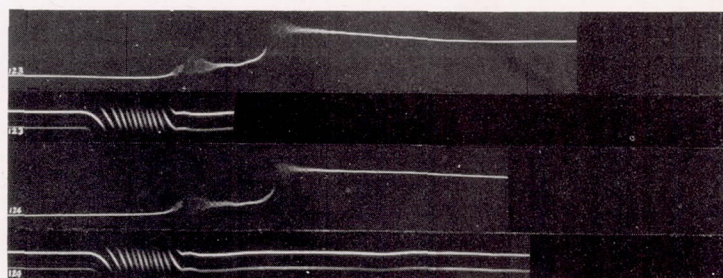
Figure 6.- Schematic diagram of rapid compression apparatus.



(a) Lead, 0 milliliter per gallon.



(b) Lead, 0.5 milliliter per gallon.



0.005 sec

(c) Lead, 1 milliliter per gallon.

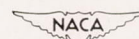
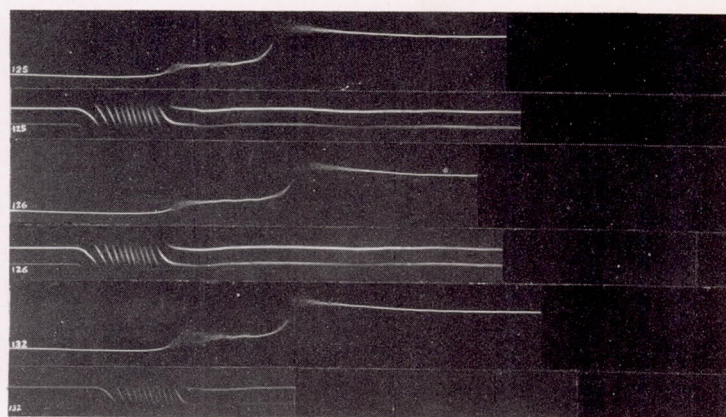
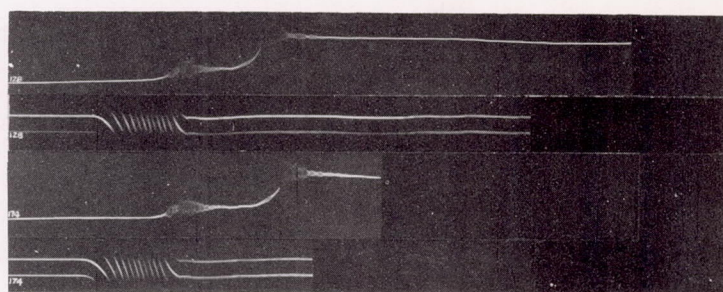


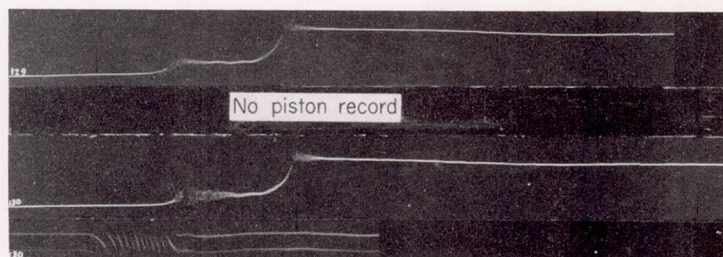
Figure 7.- Series 1 tests - the effect of tetraethyl lead on the pressure-time history of isooctane. Fuel-air ratio, 0.067 (chemically correct); compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.



(d) Lead, 2 milliliters per gallon.



(e) Lead, 4 milliliters per gallon.



0.005 sec

(f) Lead, 8 milliliters per gallon.

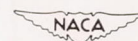


Figure 7.- Concluded.

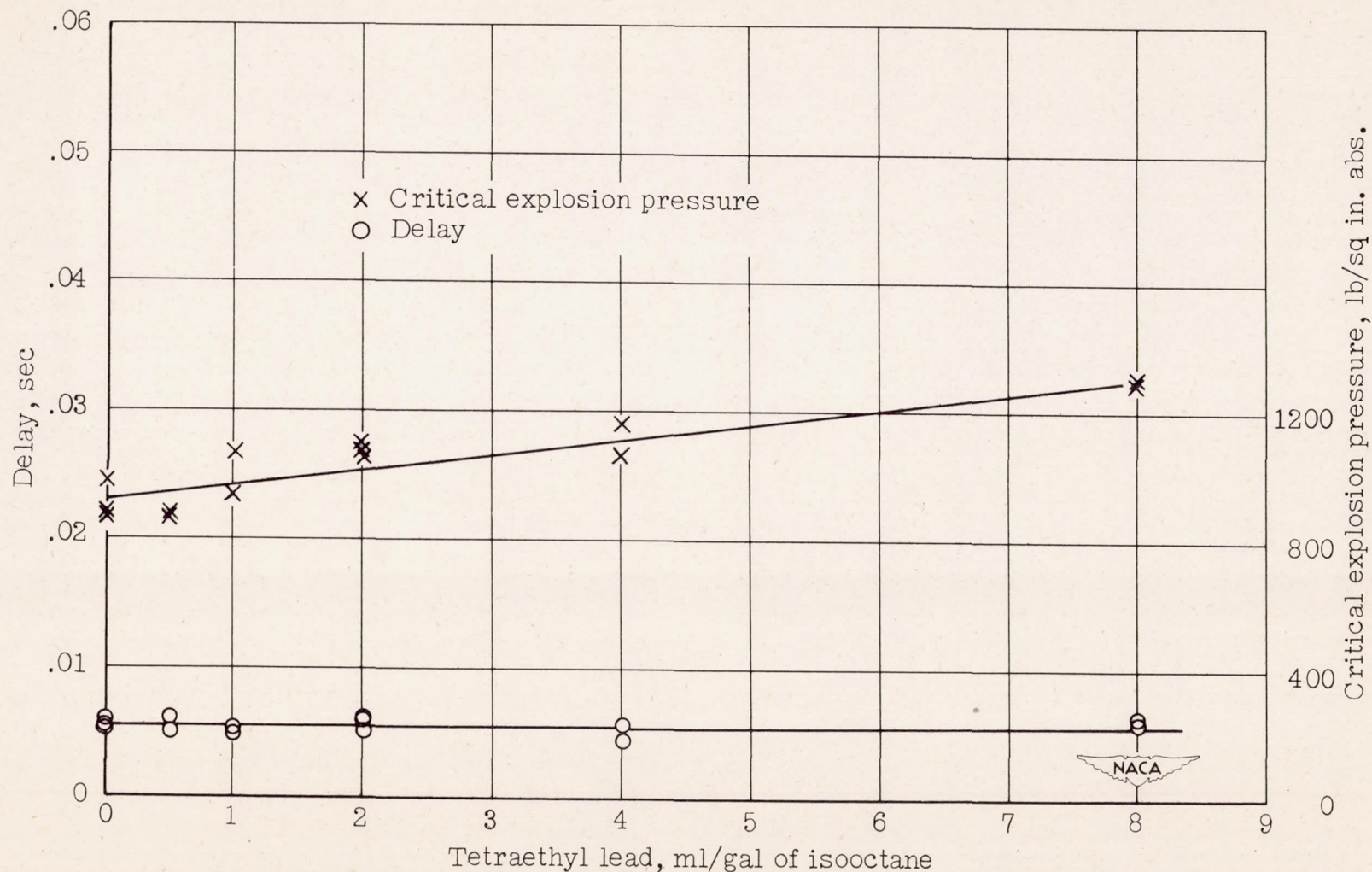
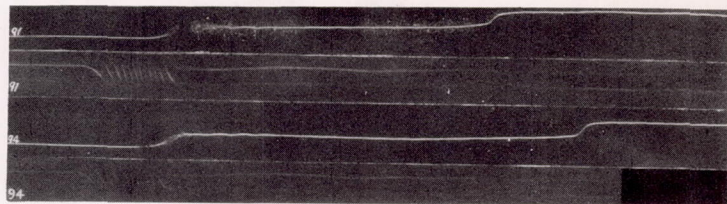
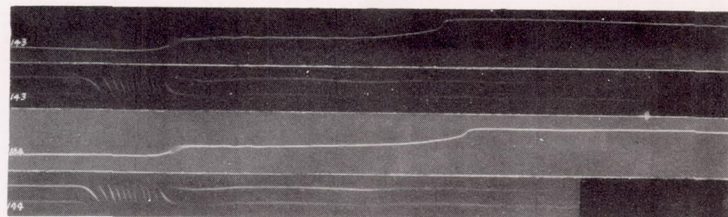


Figure 8.- Series 1 tests - the effect of tetraethyl lead on the delay and critical explosion pressure of isooctane. Fuel-air ratio, 0.067 (chemically correct); compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

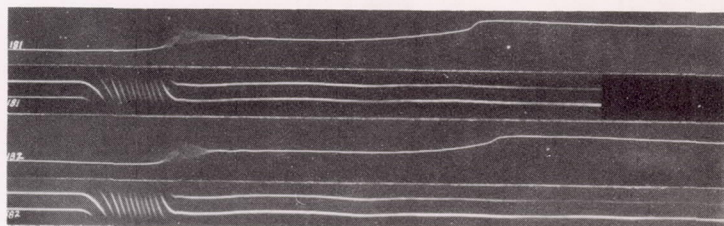
Lead, 0 ml/gal



Lead, 2 ml/gal

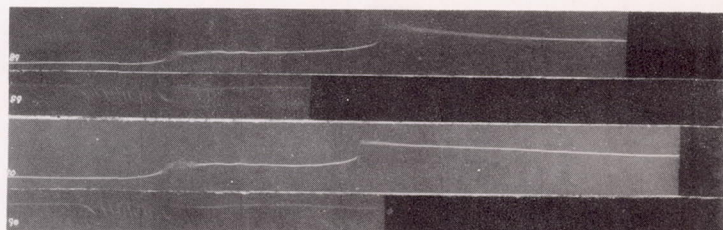


Lead, 4 ml/gal

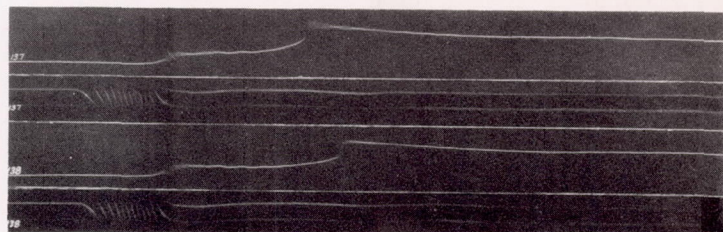


(a) Fuel-air ratio, 0.030.

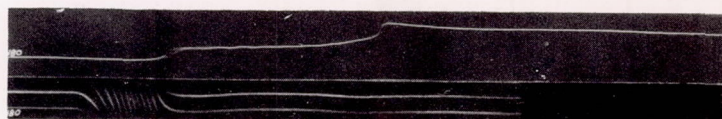
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(b) Fuel-air ratio, 0.040.

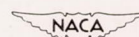
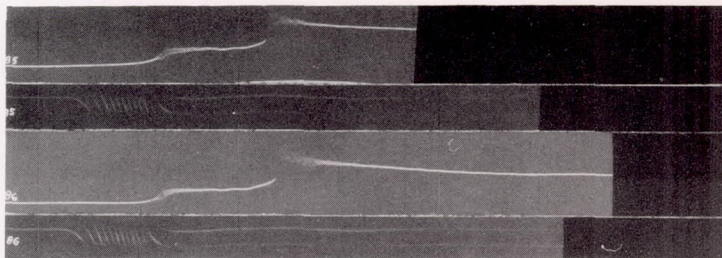
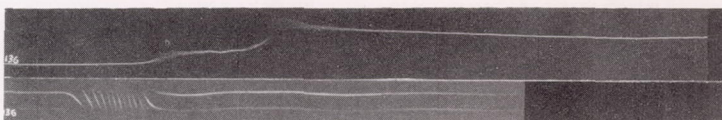


Figure 9.- Series 2 tests - the effect of tetraethyl lead on the pressure-time history of isooctane at various fuel-air ratios. Compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

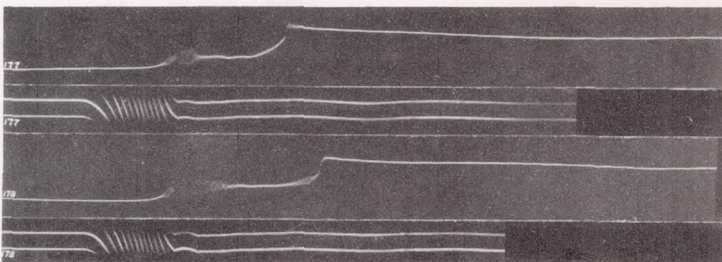
Lead, 0 ml/gal



Lead, 2 ml/gal

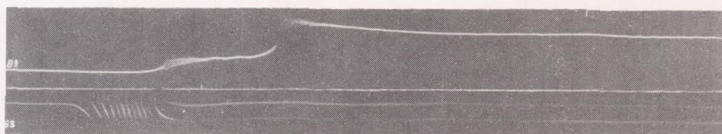


Lead, 4 ml/gal

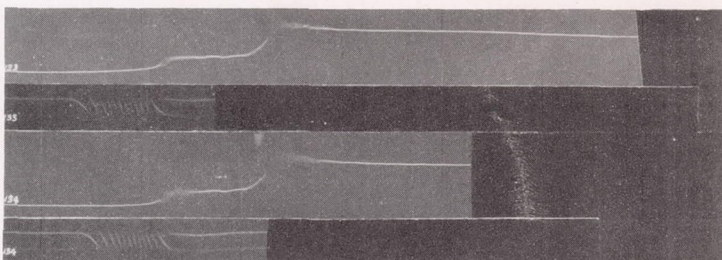


(c) Fuel-air ratio, 0.050.

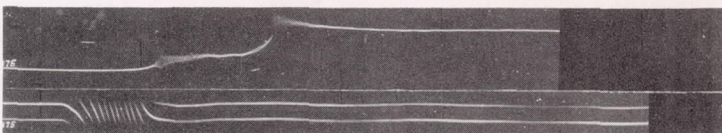
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(d) Fuel-air ratio, 0.060.

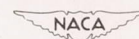
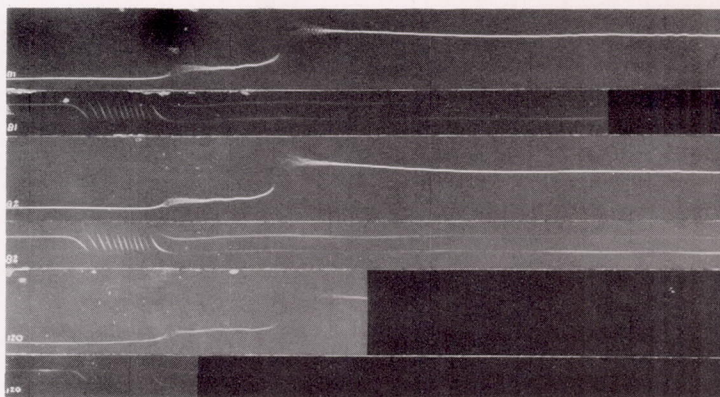
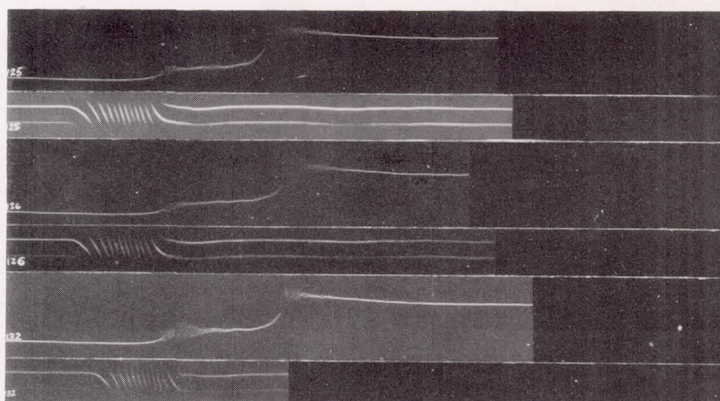


Figure 9.- Continued.

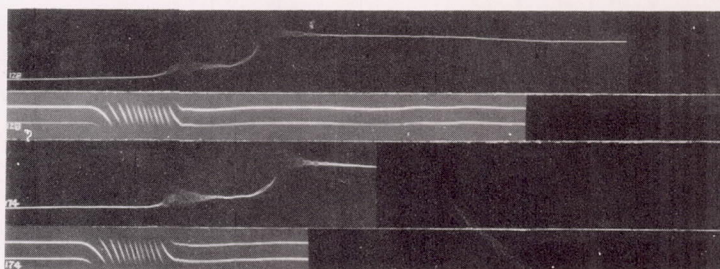
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(e) Fuel-air ratio, 0.067.

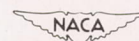
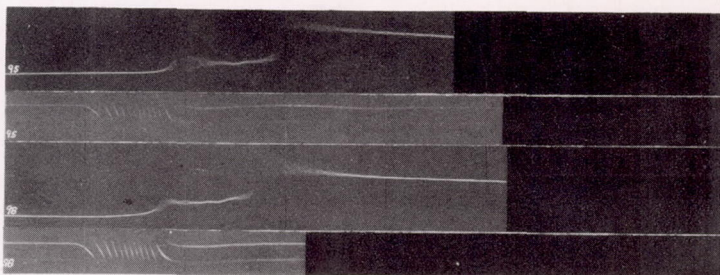
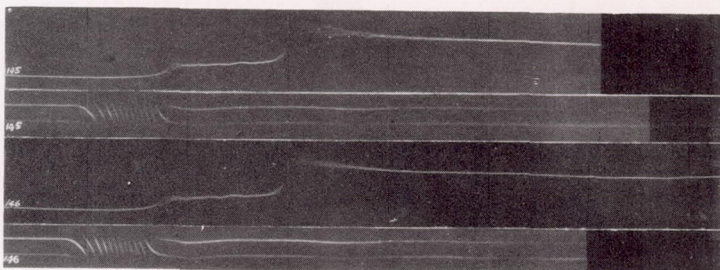


Figure 9.- Continued.

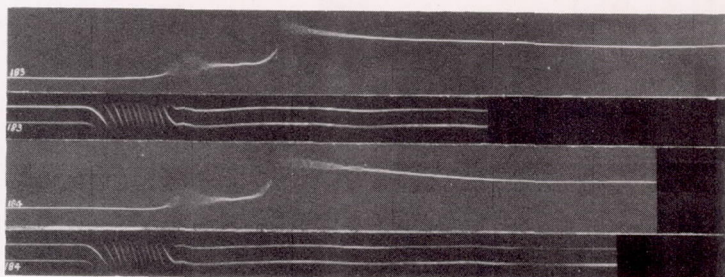
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(f) Fuel-air ratio, 0.078.

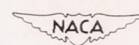
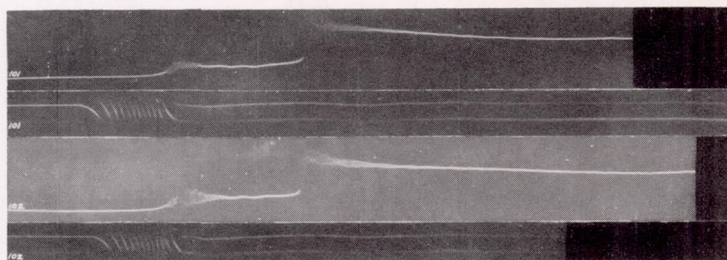
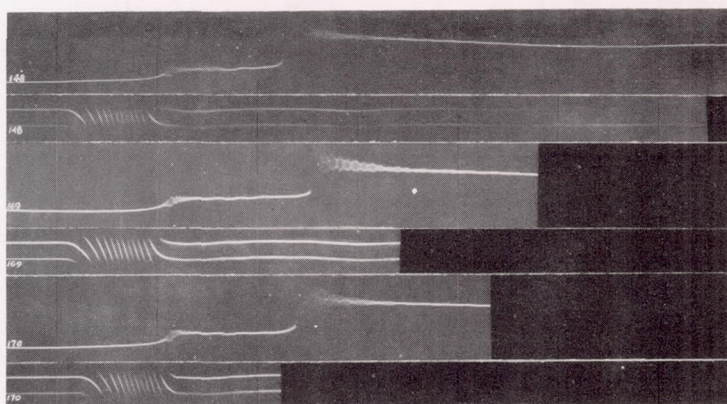


Figure 9.- Continued.

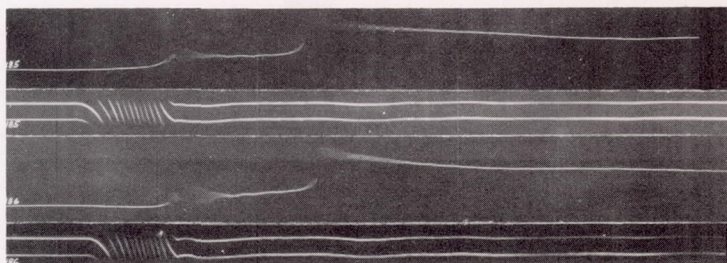
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(g) Fuel-air ratio, 0.095.

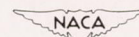
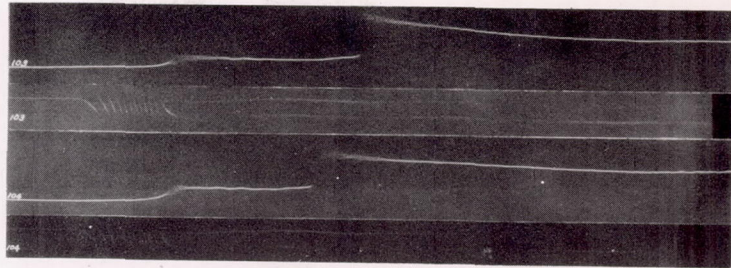
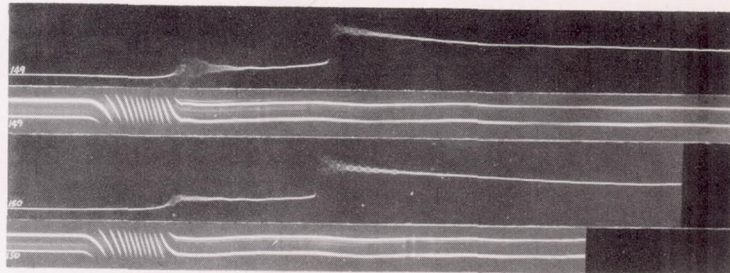


Figure 9.- Continued.

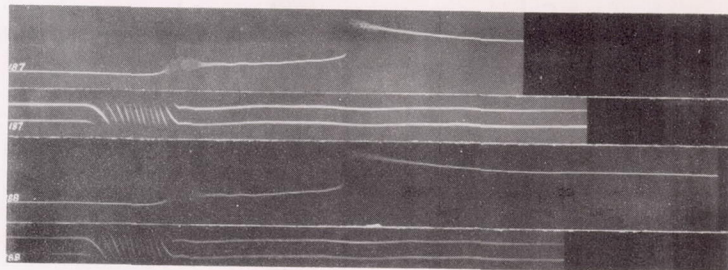
Lead, 0 ml/gal



Lead, 2 ml/gal

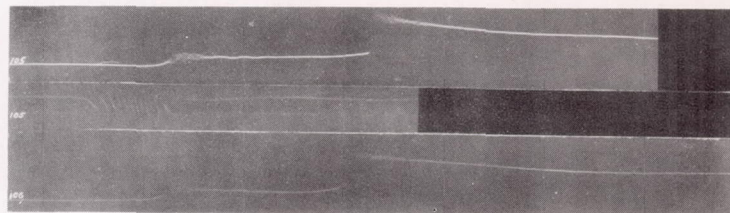


Lead, 4 ml/gal

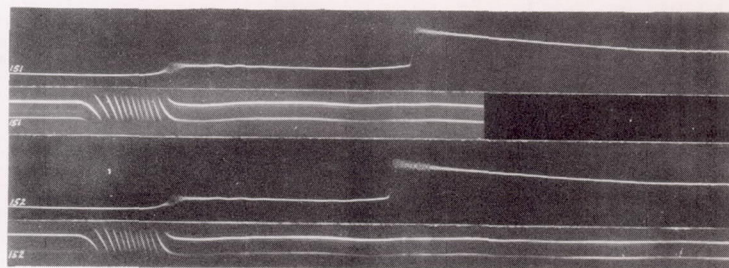


(h) Fuel-air ratio, 0.110.

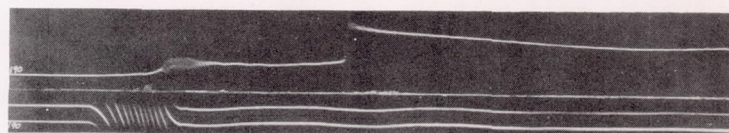
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(i) Fuel-air ratio, 0.120.

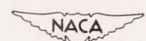
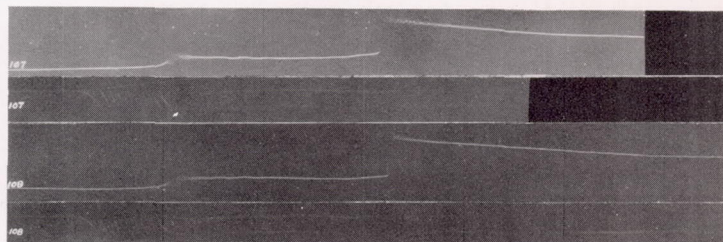
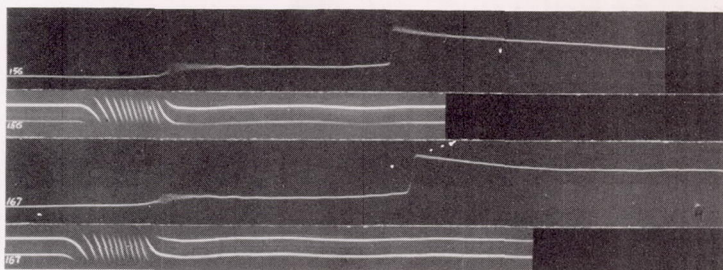


Figure 9.- Continued.

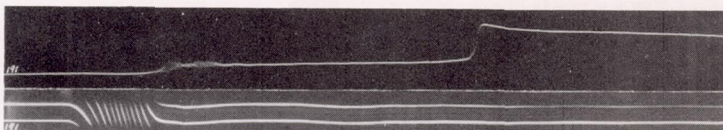
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



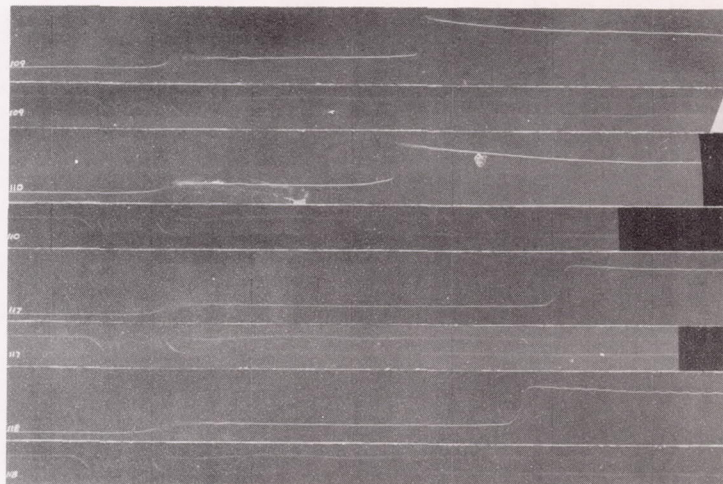
0.005 sec

(j) Fuel-air ratio, 0.130.

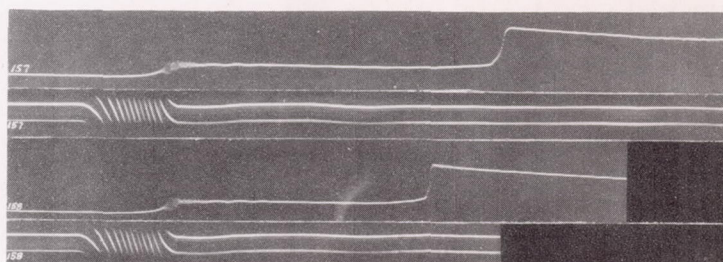


Figure 9.- Continued.

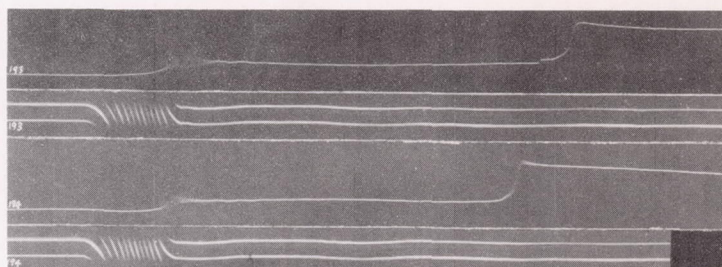
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



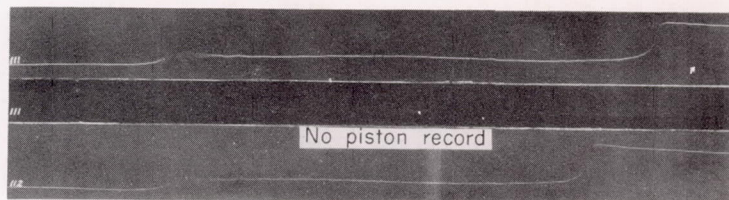
0.005 sec

(k) Fuel-air ratio, 0.140.

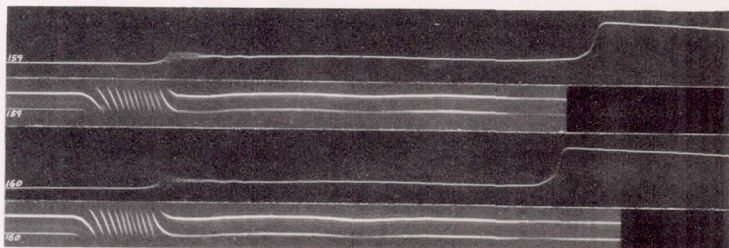


Figure 9.- Continued.

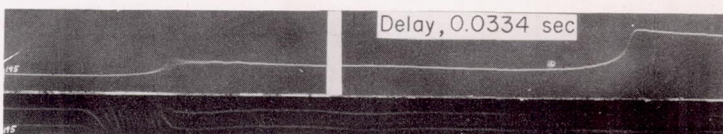
Lead, 0 ml/gal



Lead, 2 ml/gal

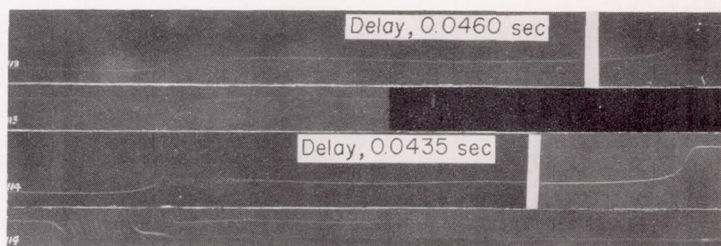


Lead, 4 ml/gal

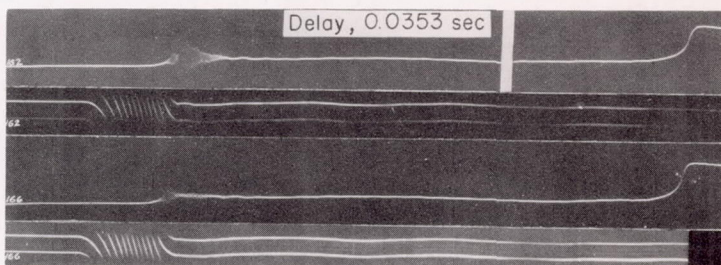


(l) Fuel-air ratio, 0.150.

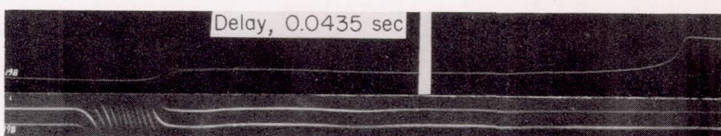
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(m) Fuel-air ratio, 0.160.

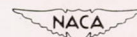
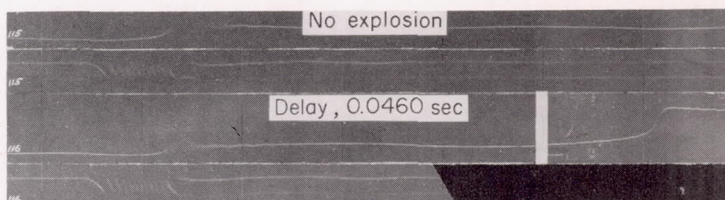
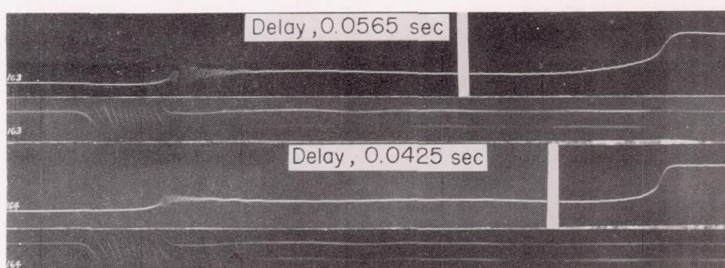


Figure 9.- Continued.

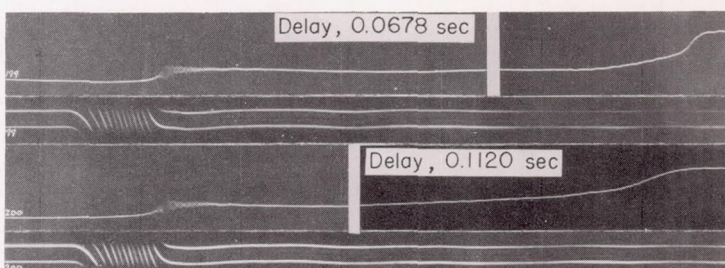
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(n) Fuel-air ratio, 0.170.

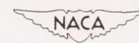


Figure 9.- Concluded.

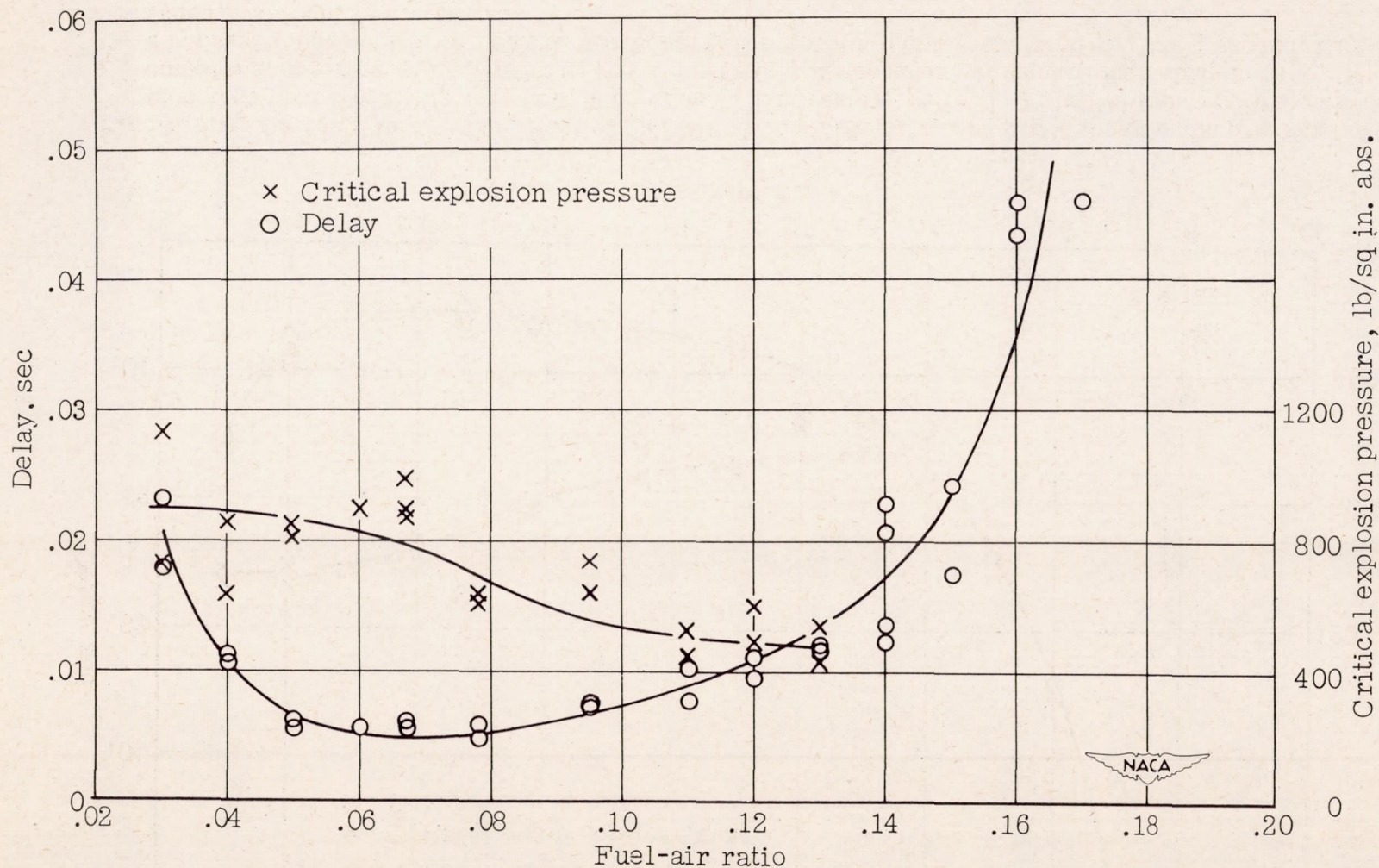


Figure 10.- Series 2 tests - the effect of fuel-air ratio on the delay and critical explosion pressure of unleaded isooctane. Compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

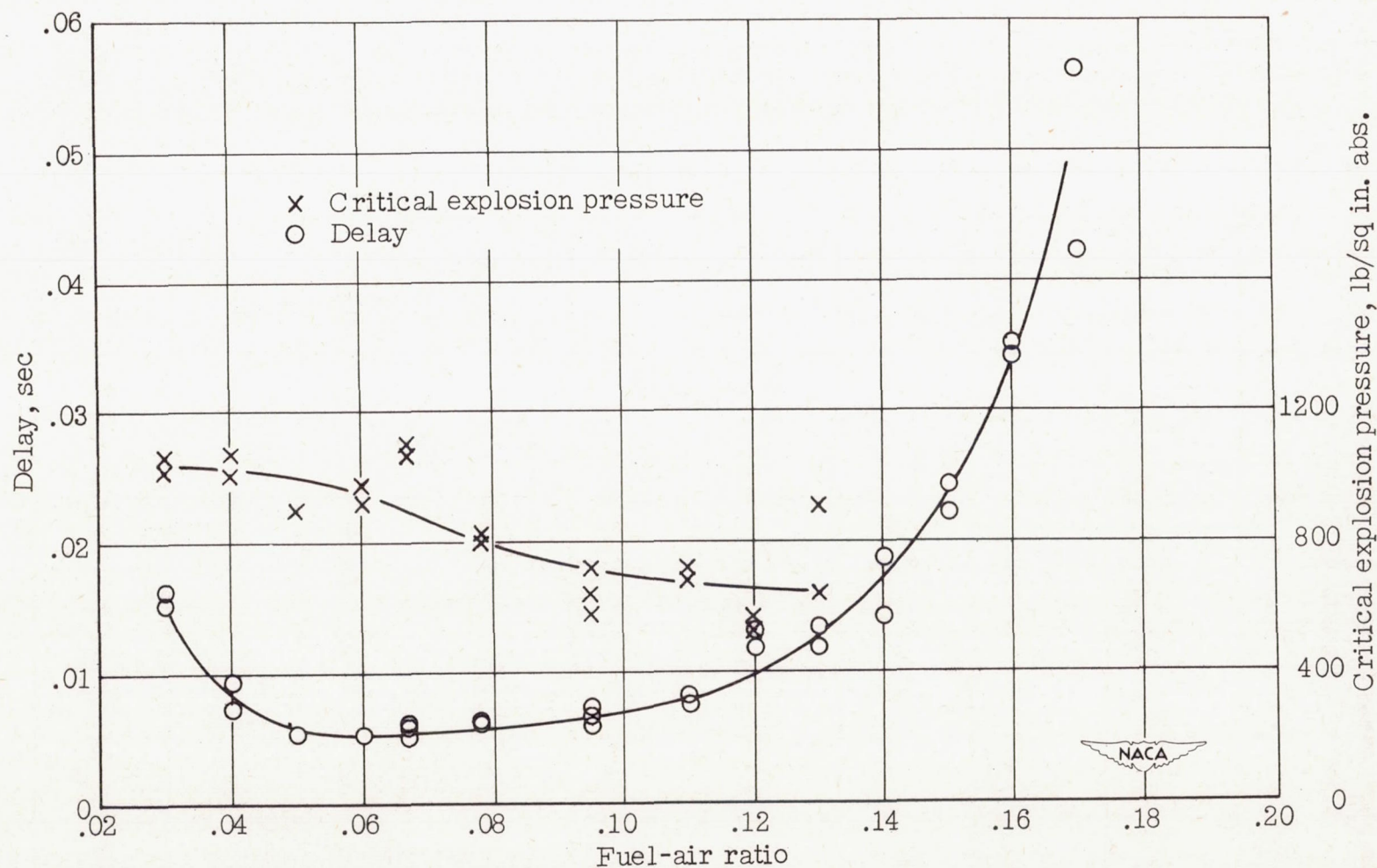


Figure 11.- Series 2 tests - the effect of fuel-air ratio on the delay and critical explosion pressure of isooctane plus 2 milliliters of lead per gallon. Compression ratio, 11.7; initial temperature, 609°R ; compression temperature, 1340°R ; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

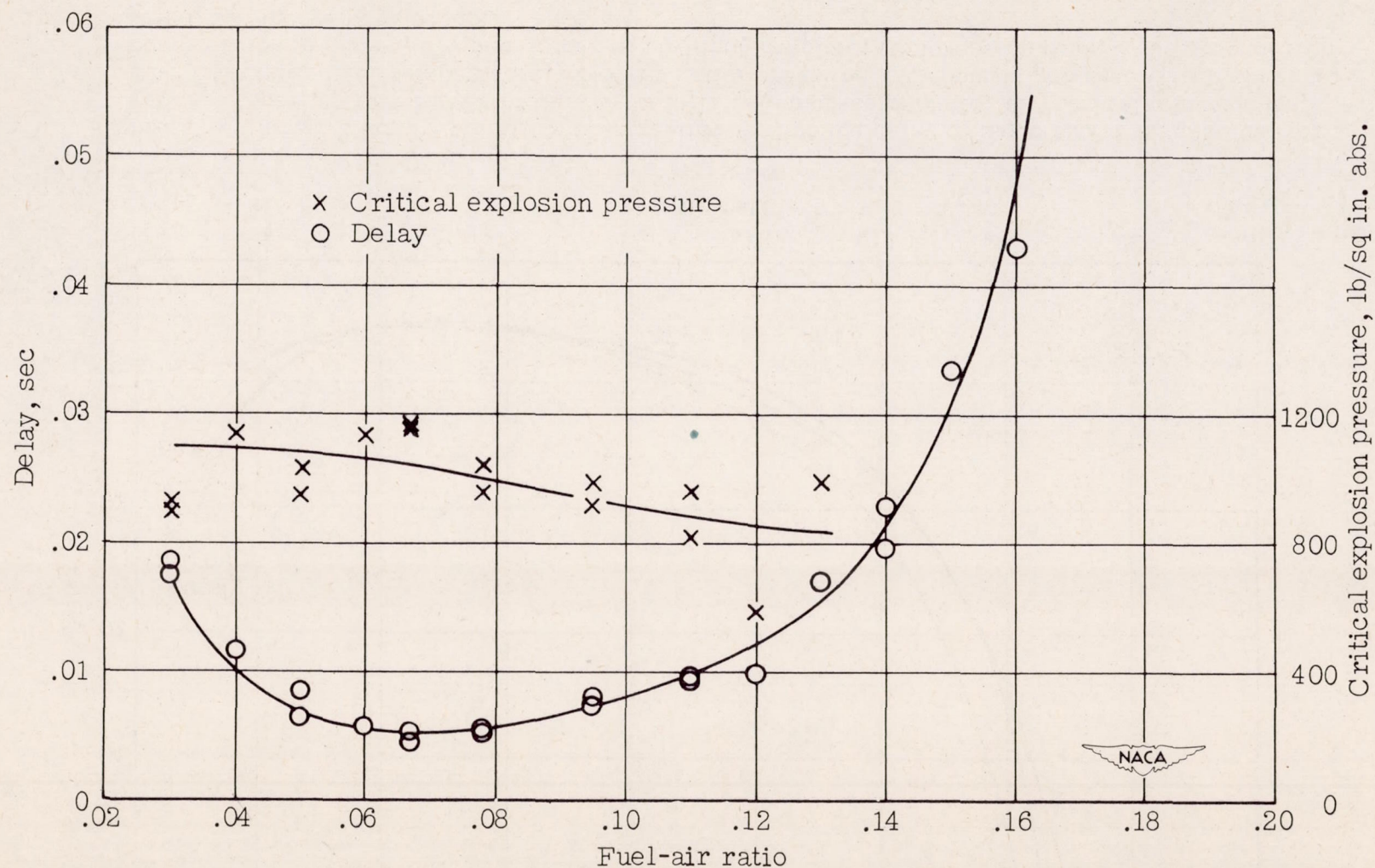


Figure 12.- Series 2 tests - the effect of fuel-air ratio on the delay and critical explosion pressure of isooctane plus 4 milliliters of lead per gallon. Compression ratio, 11.7; initial temperature, 609°R ; compression temperature, 1340°R ; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

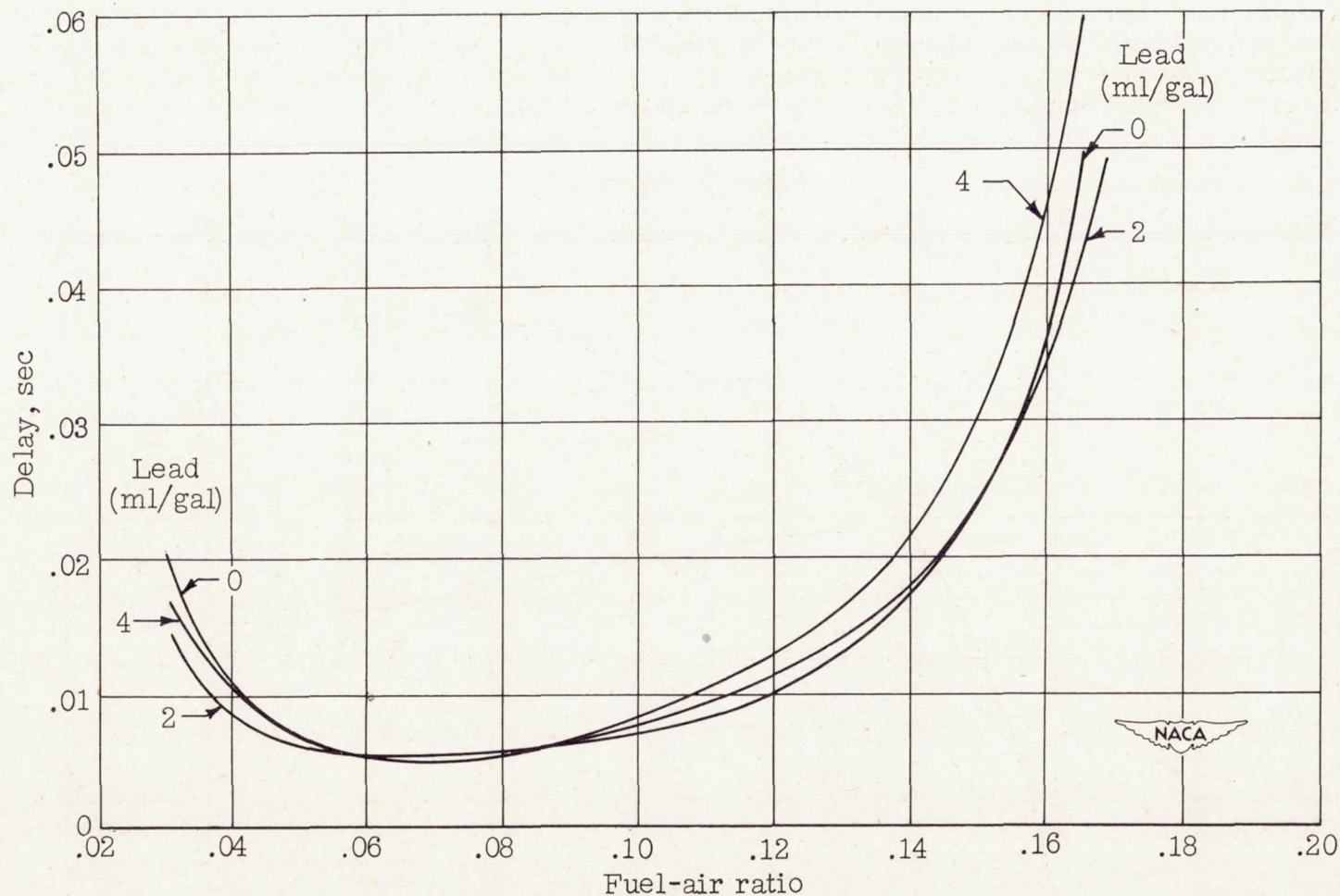


Figure 13.- Series 2 tests - the effect of tetraethyl lead on the delay of isooctane at various fuel-air ratios. Superimposed curves of figures 10 to 12. Compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

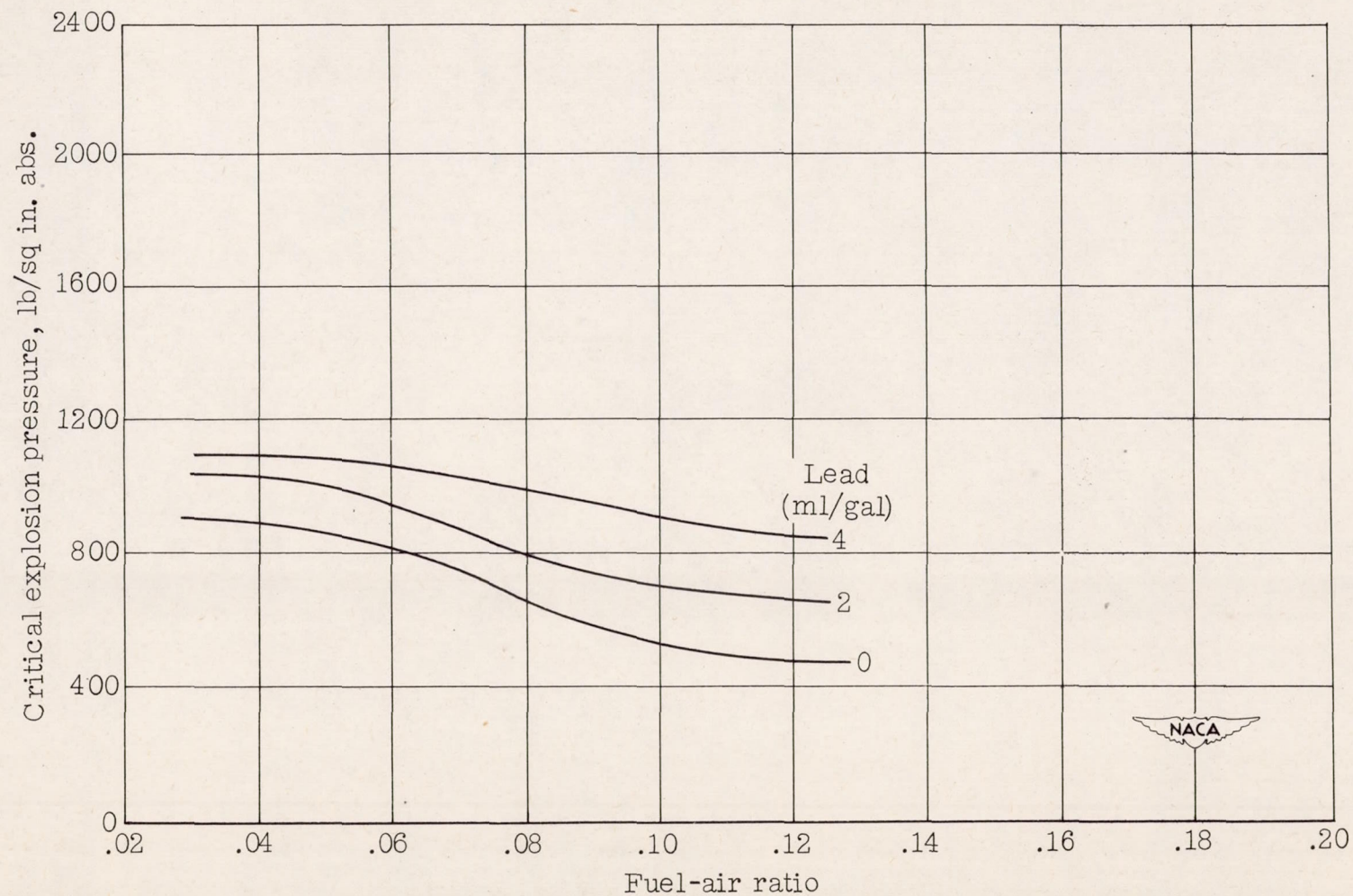
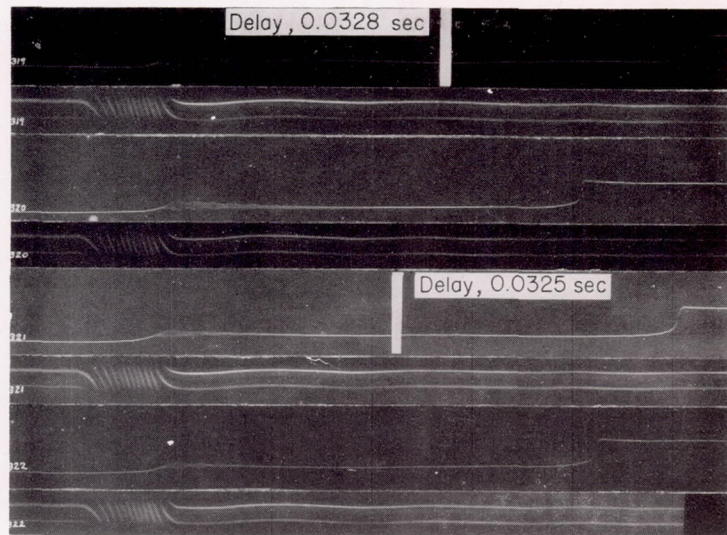
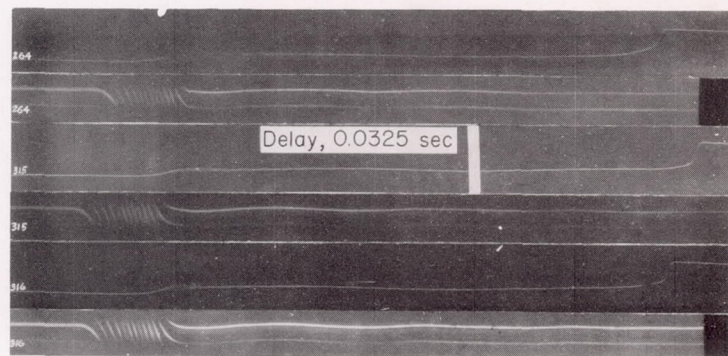


Figure 14.- Series 2 tests - the effect of tetraethyl lead on the critical explosion pressure of isooctane at various fuel-air ratios. Superimposed curves of figures 10 to 12. Compression ratio, 11.7; initial temperature, 609°R ; compression temperature, 1340°R ; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

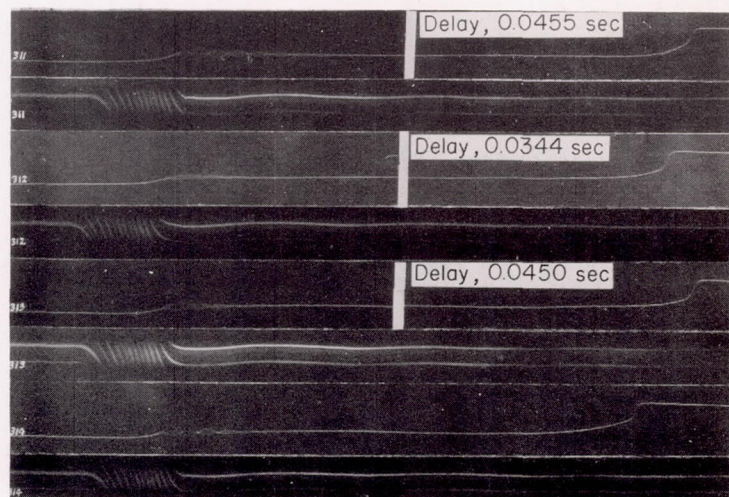
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(a) Compression ratio, 8.0.

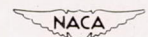
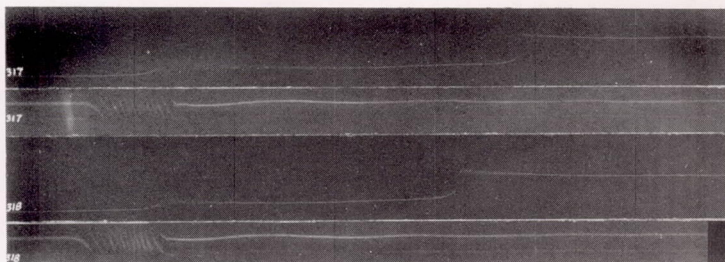
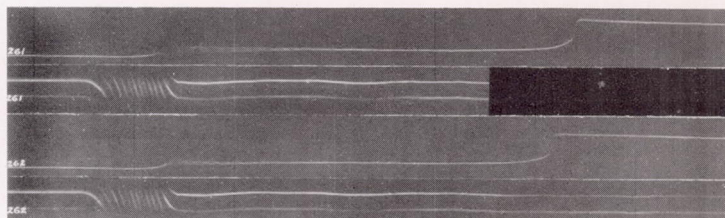


Figure 15.- Series 3 tests - the effect of tetraethyl lead on the pressure-time history of isooctane at various compression ratios. Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R; initial pressure, 14.7 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

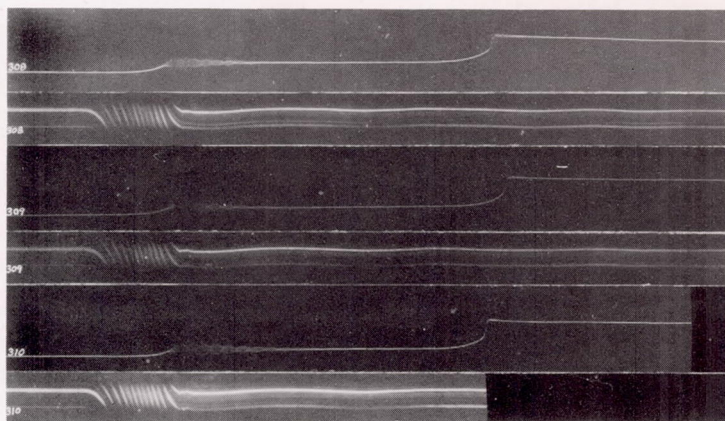
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(b) Compression ratio, 8.5.

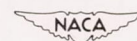
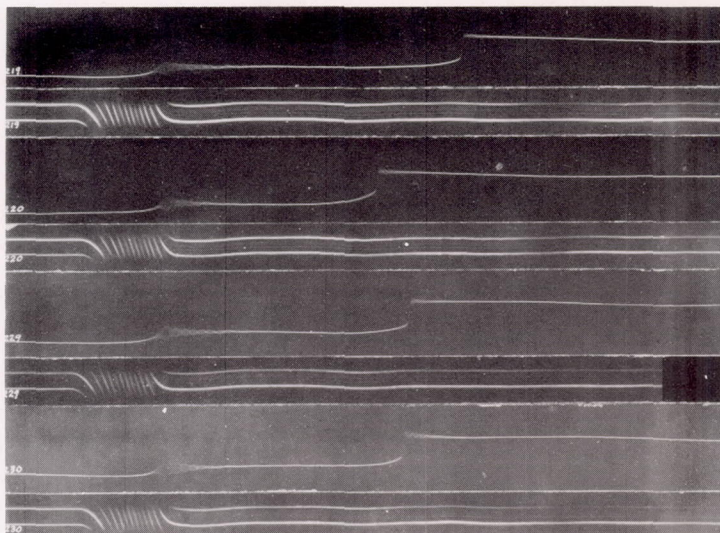
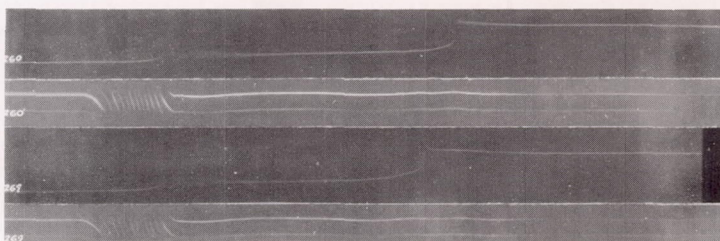


Figure 15.- Continued.

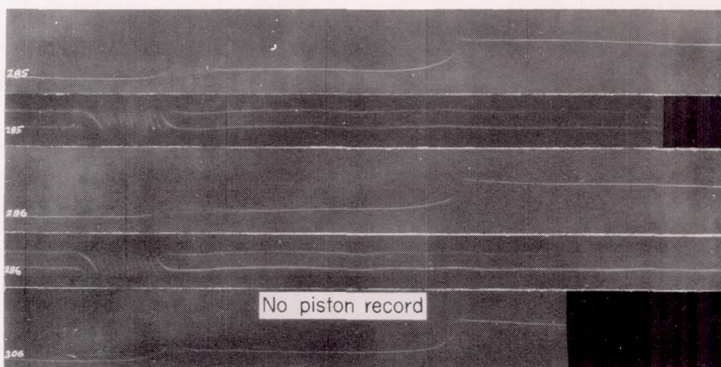
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



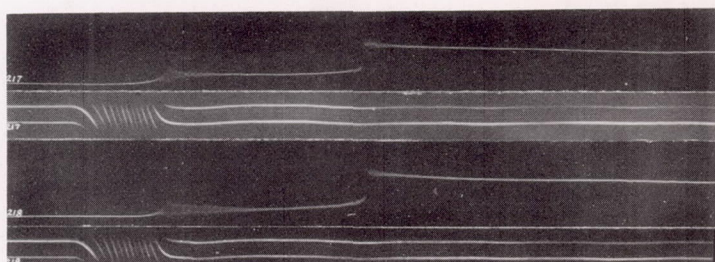
0.005 sec

(c) Compression ratio, 8.9.

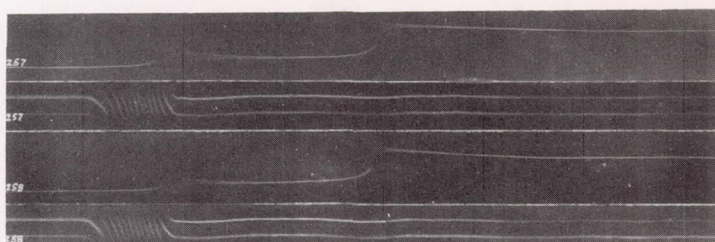


Figure 15.- Continued.

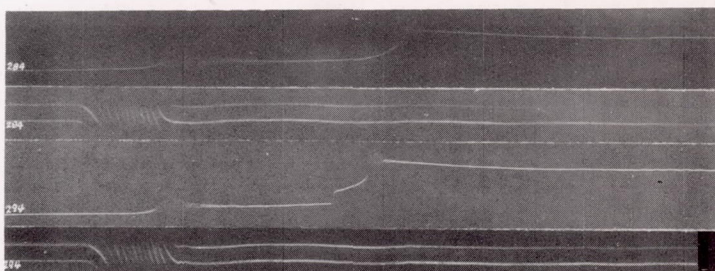
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(d) Compression ratio, 9.4.

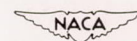
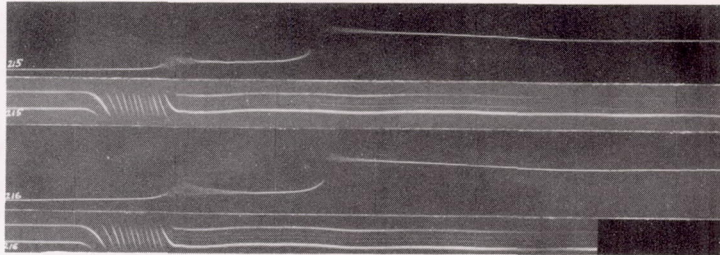
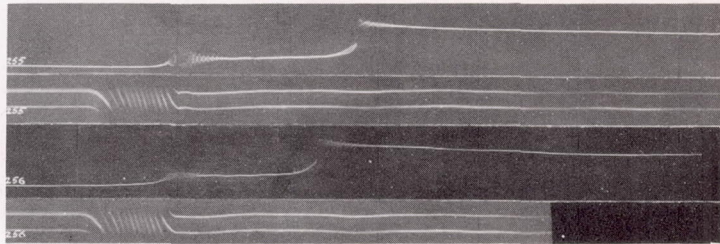


Figure 15.- Continued.

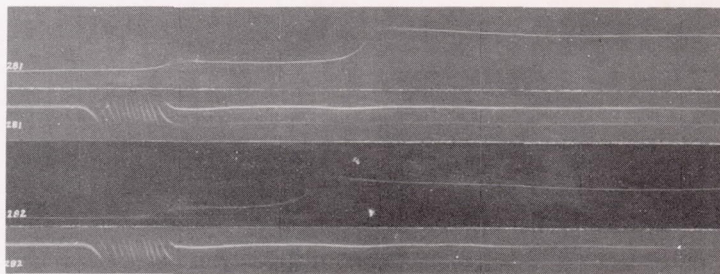
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



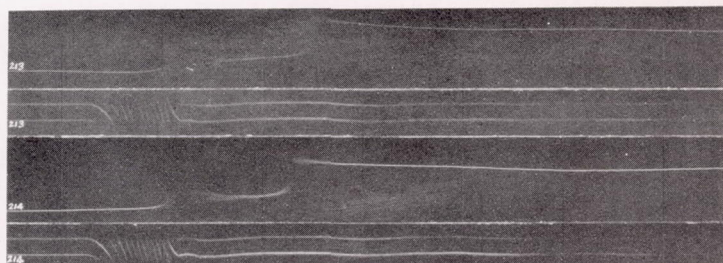
0.005 sec

(e) Compression ratio, 10.0.

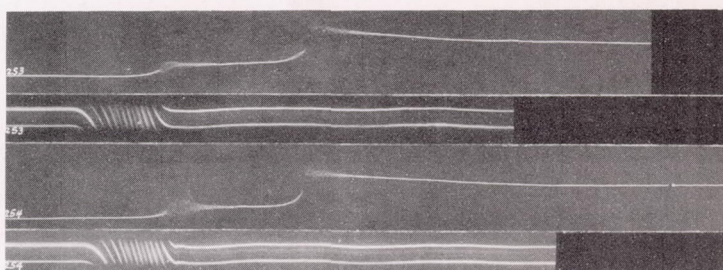


Figure 15.- Continued.

Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(f) Compression ratio, 10.7.

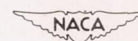
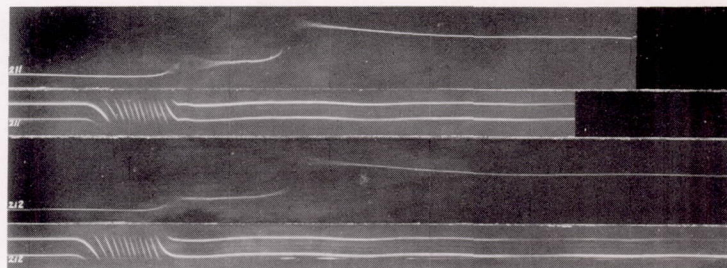
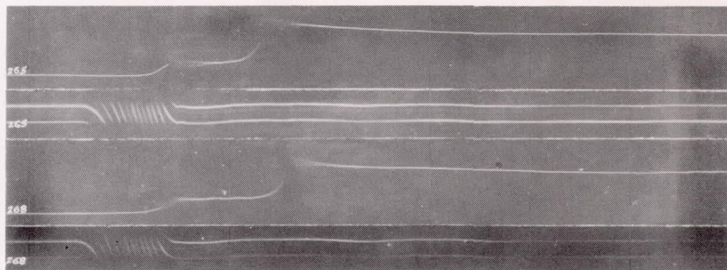


Figure 15.- Continued.

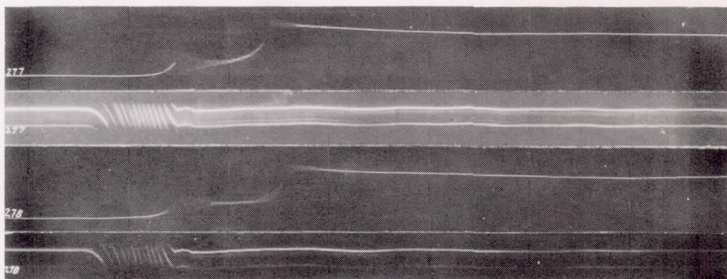
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(g) Compression ratio, 11.5.

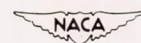
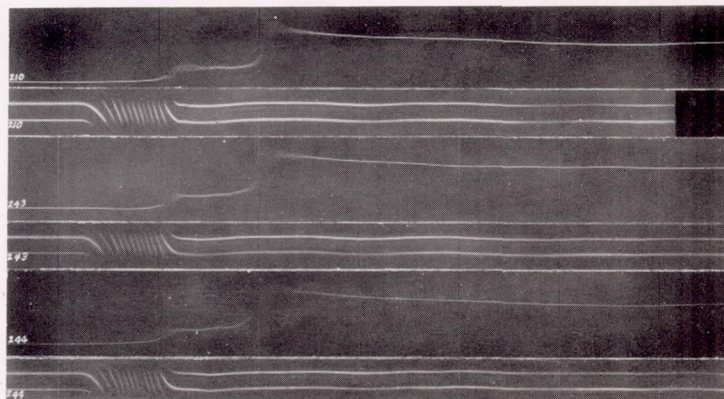
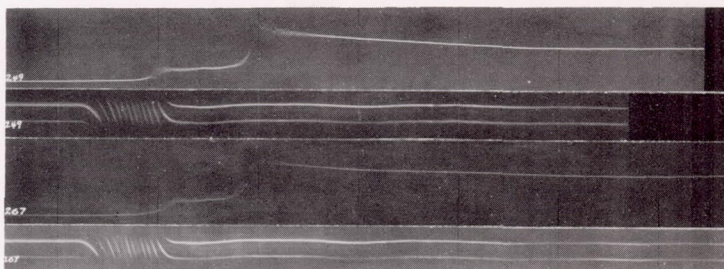


Figure 15.- Continued.

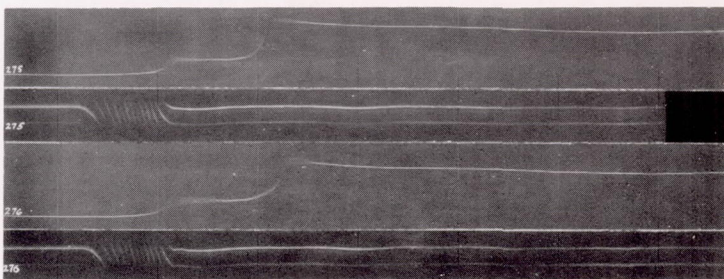
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(h) Compression ratio, 12.4.

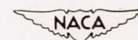
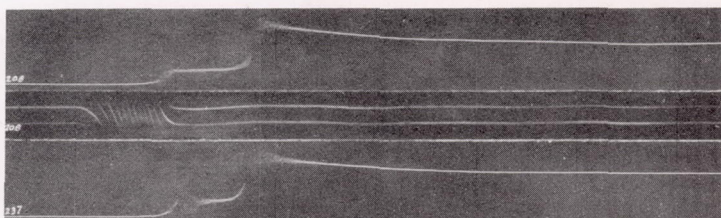
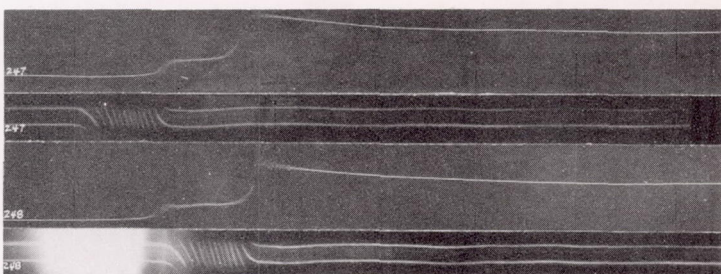


Figure 15.- Continued.

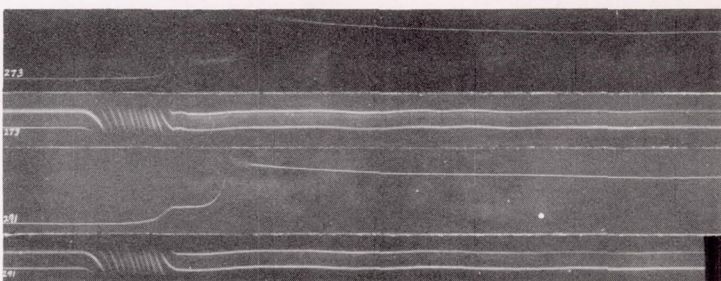
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(i) Compression ratio, 13.5.

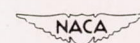
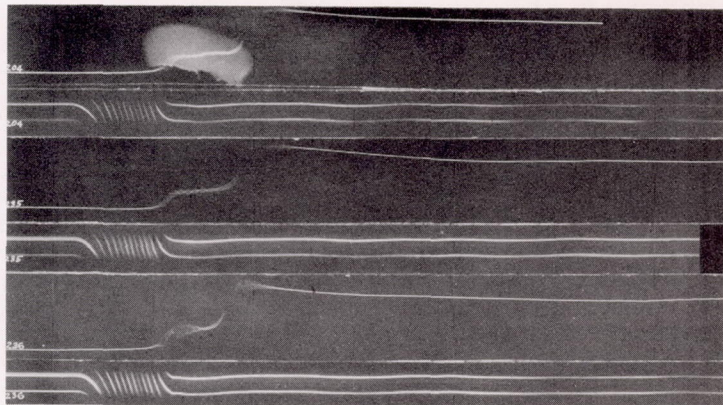
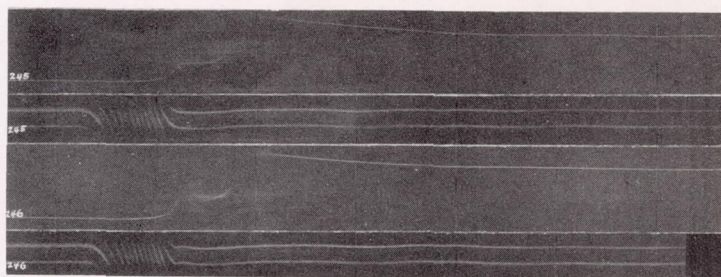


Figure 15.- Continued.

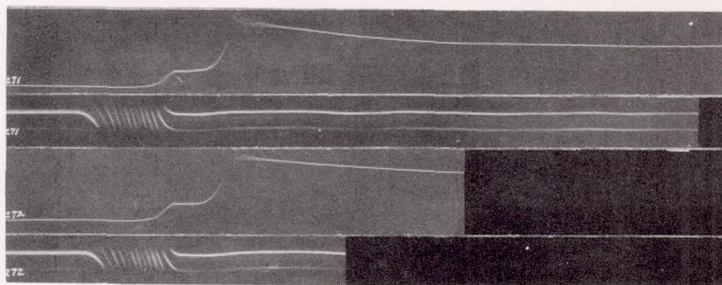
Lead, 0 ml/gal



Lead, 2 ml/gal



Lead, 4 ml/gal



0.005 sec

(j) Compression ratio, 14.9.

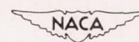


Figure 15.- Concluded.

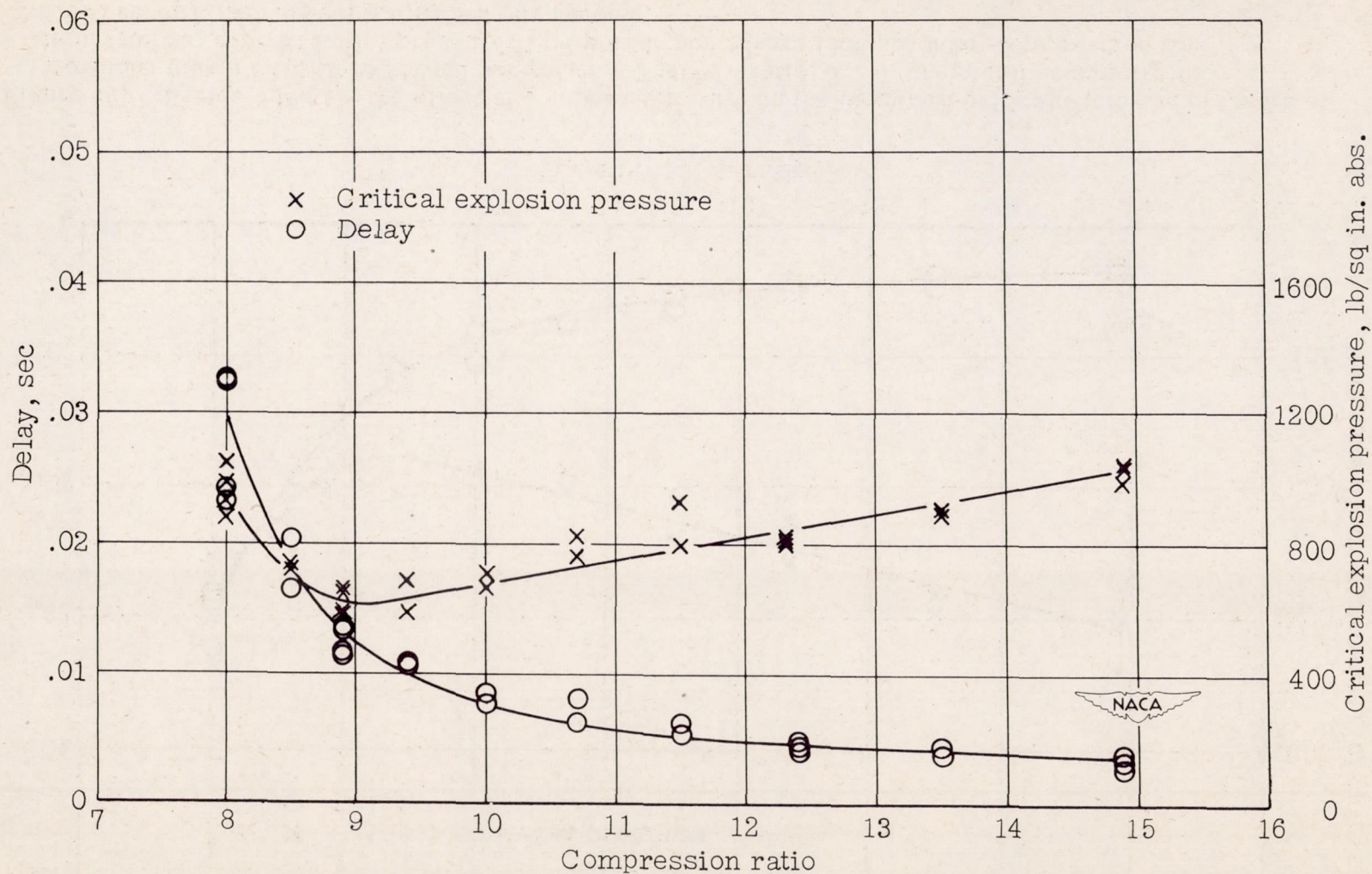


Figure 16.- Series 3 tests - the effect of compression ratio on the delay and critical explosion pressure of unleaded isooctane. Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R; initial pressure, 14.7 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

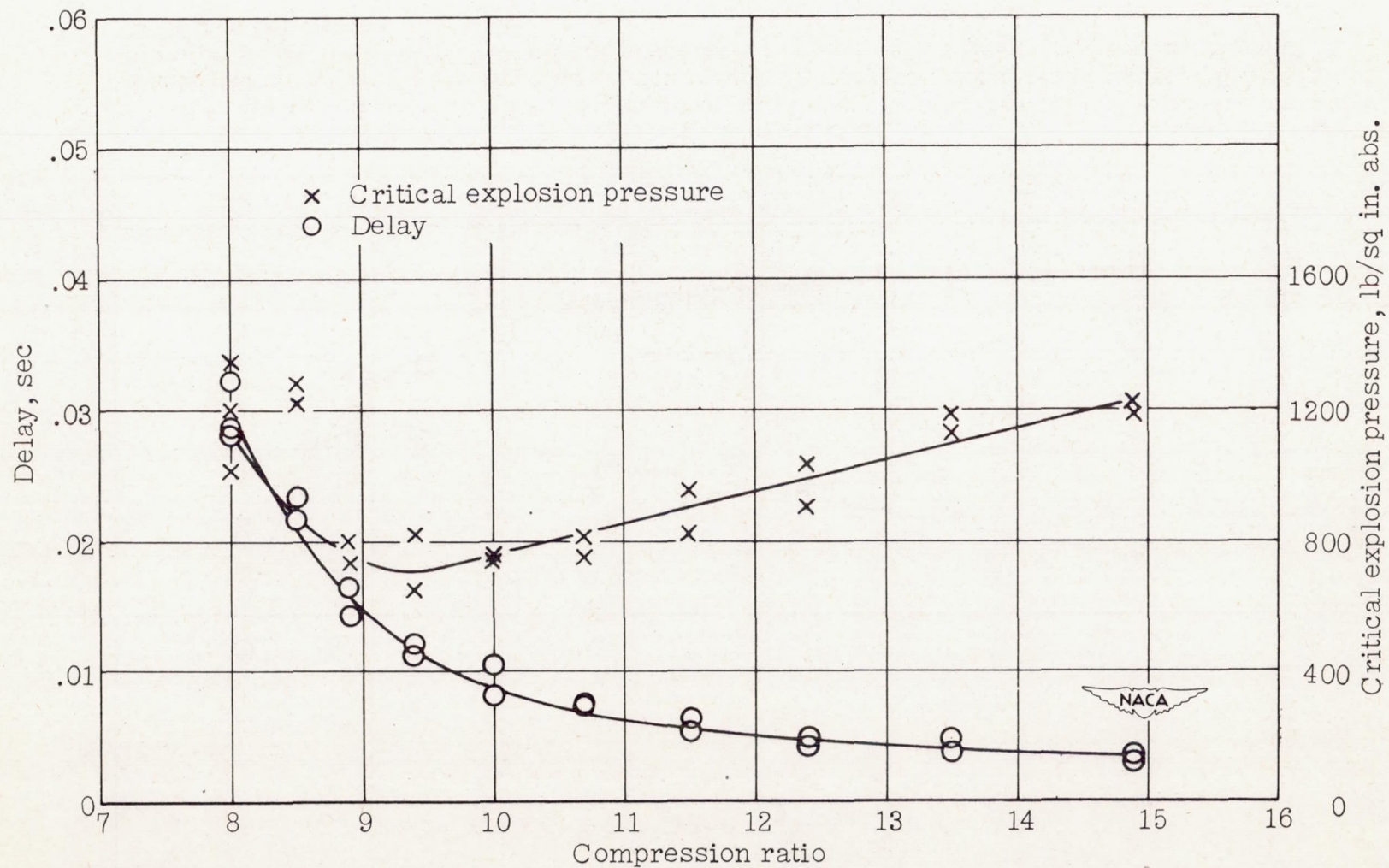


Figure 17.- Series 3 tests - the effect of compression ratio on the delay and critical explosion pressure of isooctane plus 2 milliliters of lead per gallon. Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R; initial pressure, 14.7 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

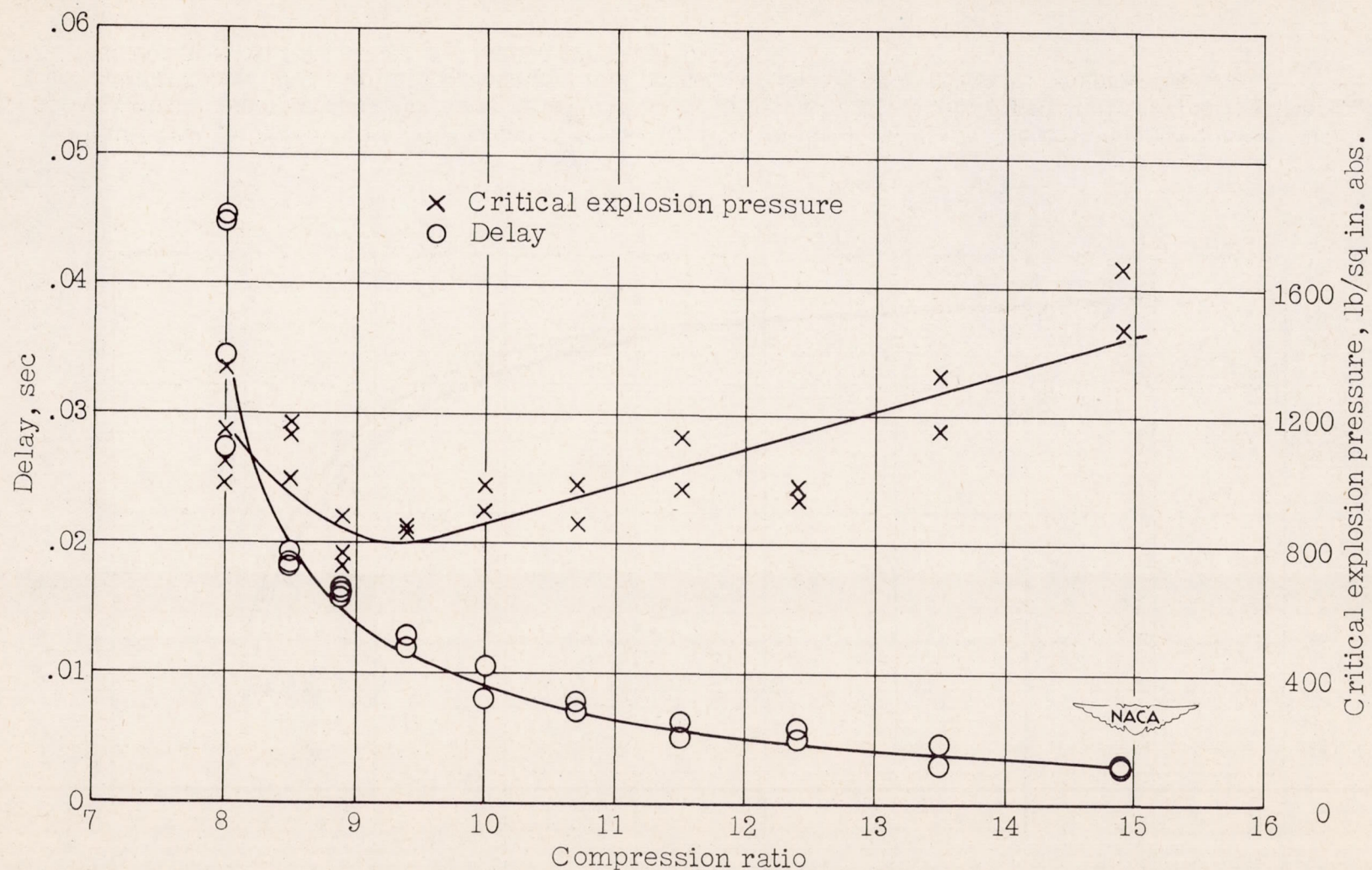


Figure 18.- Series 3 tests - the effect of compression ratio on the delay and critical explosion pressure of isooctane plus 4 milliliters of lead per gallon. Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R; initial pressure, 14.7 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

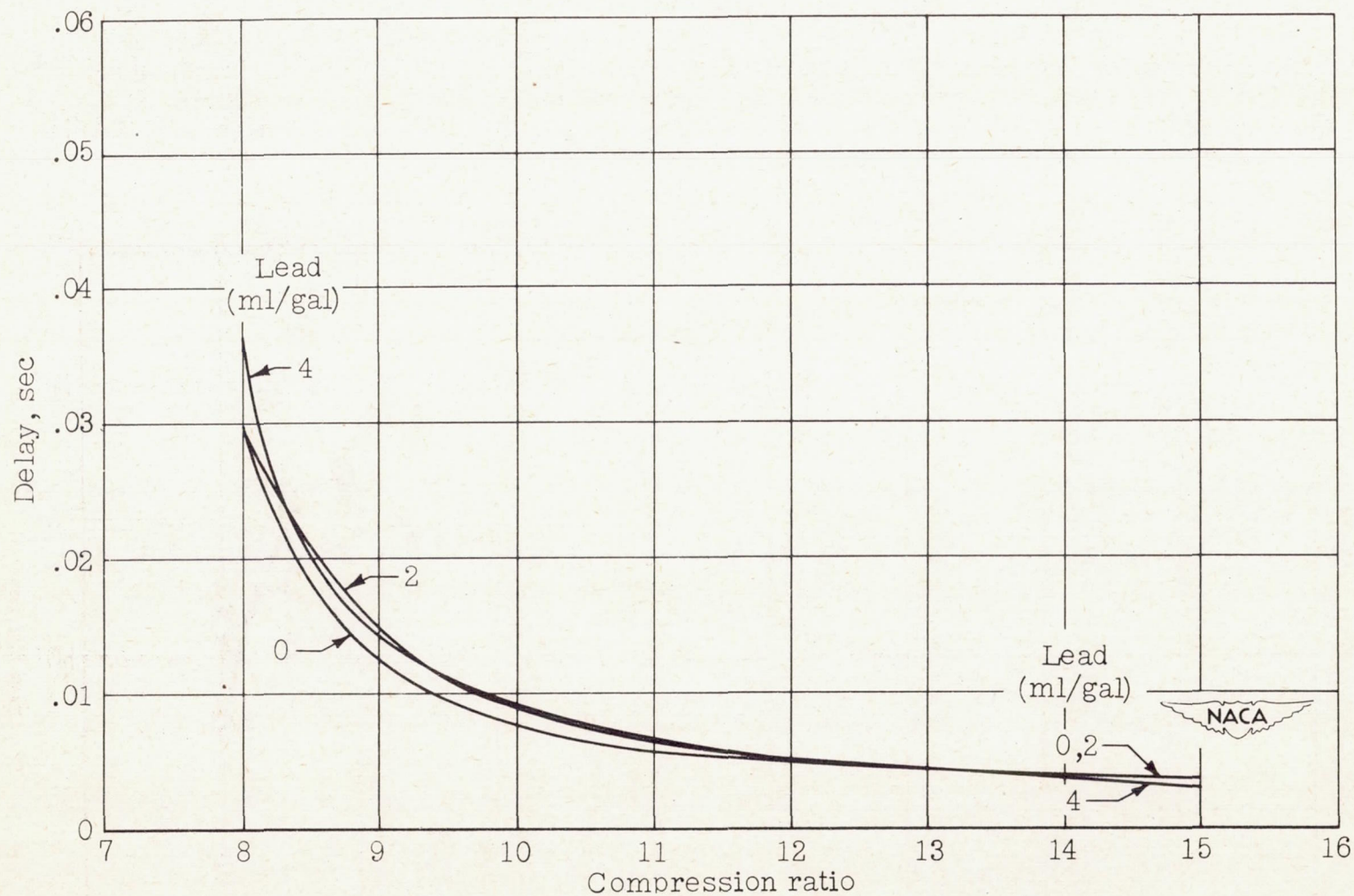


Figure 19.- Series 3 tests - the effect of tetraethyl lead on the delay of isooctane at various compression ratios. Superimposed curves of figures 16 to 18. Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R; initial pressure, 14.7 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

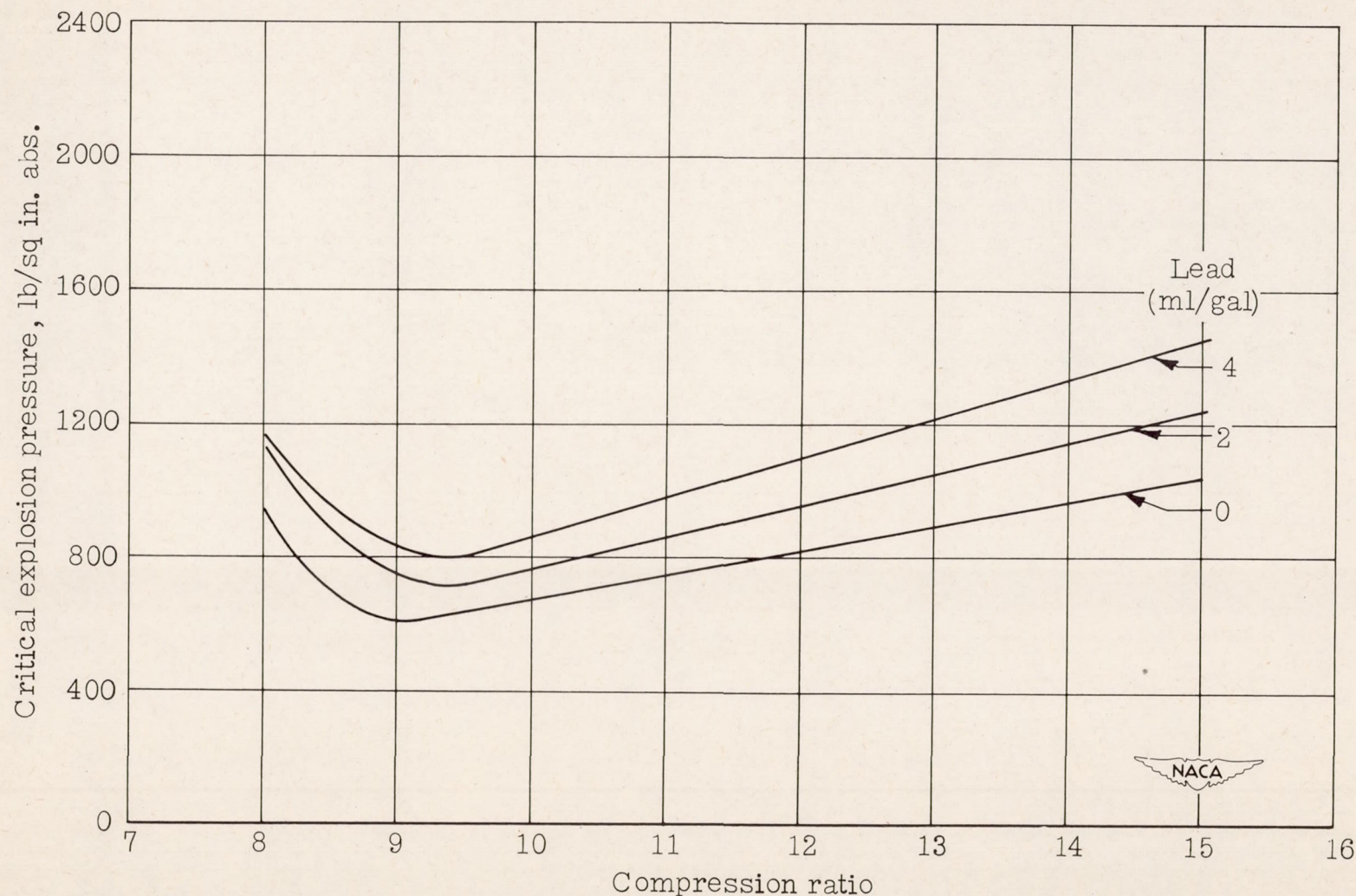
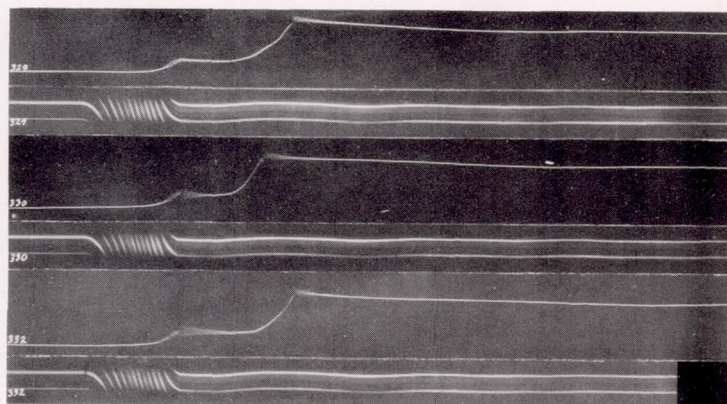
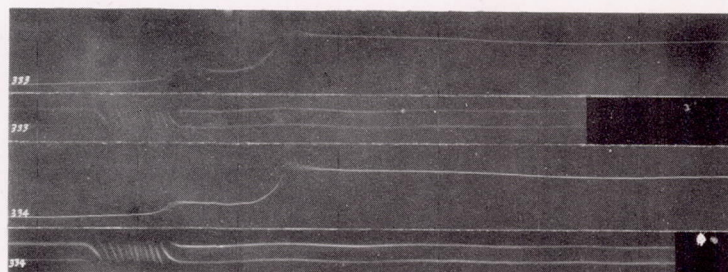


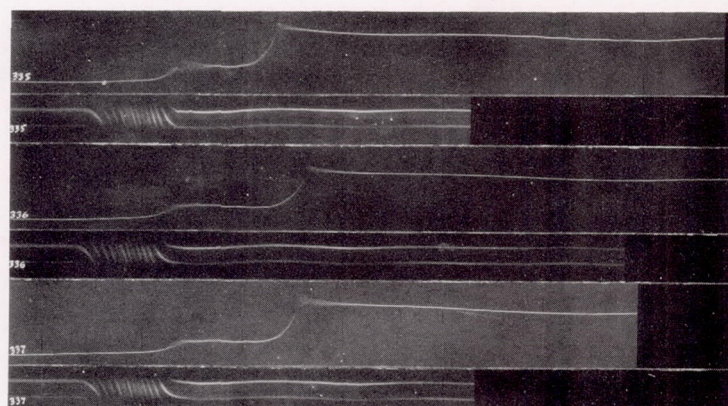
Figure 20.- Series 3 tests - the effect of tetraethyl lead on the critical explosion pressure of isooctane at various compression ratios. Superimposed curves of figures 16 to 18. Fuel-air ratio, 0.067 (chemically correct); initial temperature, 609° R; initial pressure, 14.7 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.



(a) Ethyl nitrite, 0 milliliter per gallon.



(b) Ethyl nitrite, 4 milliliters per gallon.



0.005 sec (c) Ethyl nitrite, 8 milliliters per gallon.

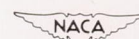
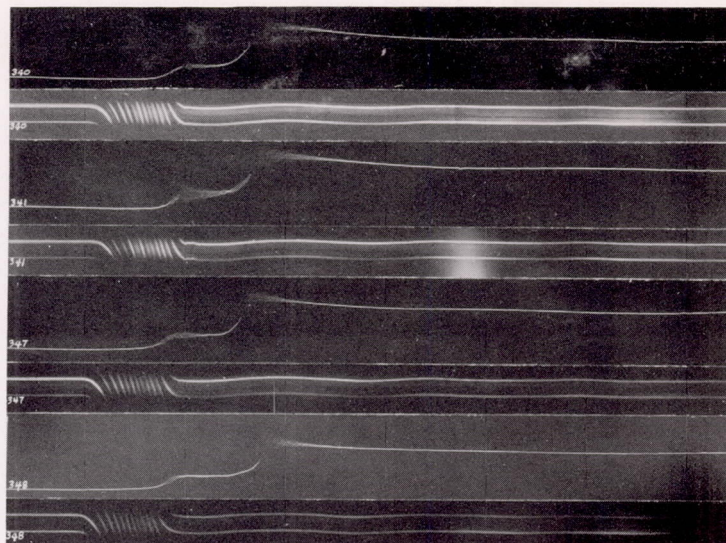
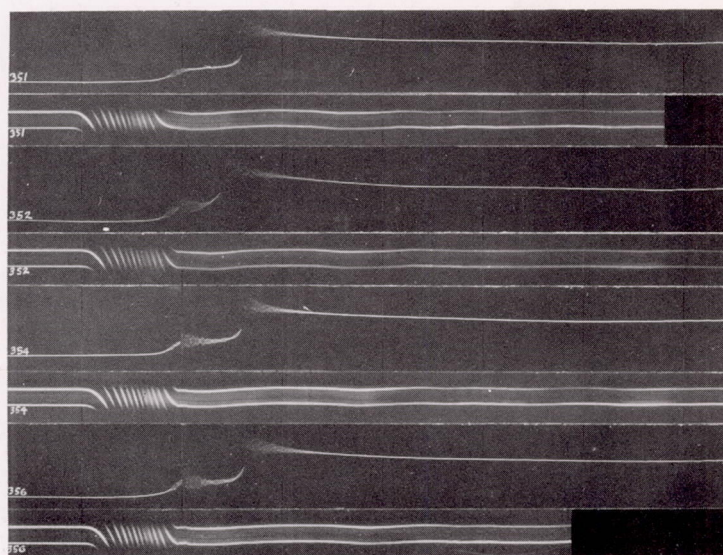


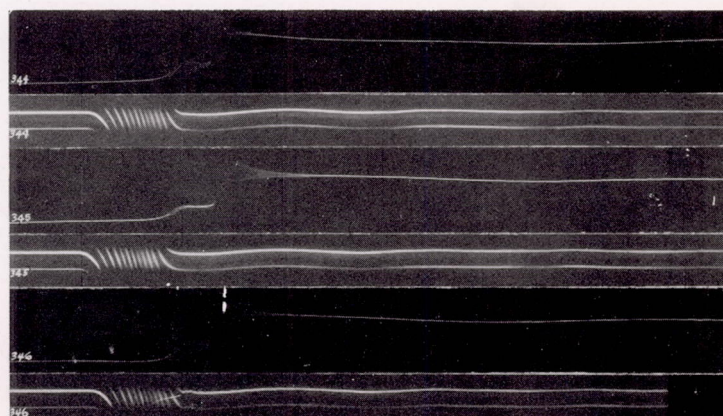
Figure 21.- Series 4 tests - the effect of ethyl nitrite on the pressure-time history of triptane. Fuel-air ratio, 0.066 (chemically correct); compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.



(d) Ethyl nitrite, 120 milliliters per gallon.

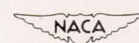


(e) Ethyl nitrite, 308 milliliters per gallon.



0.005 sec

(f) Ethyl nitrite, 488 milliliters per gallon.



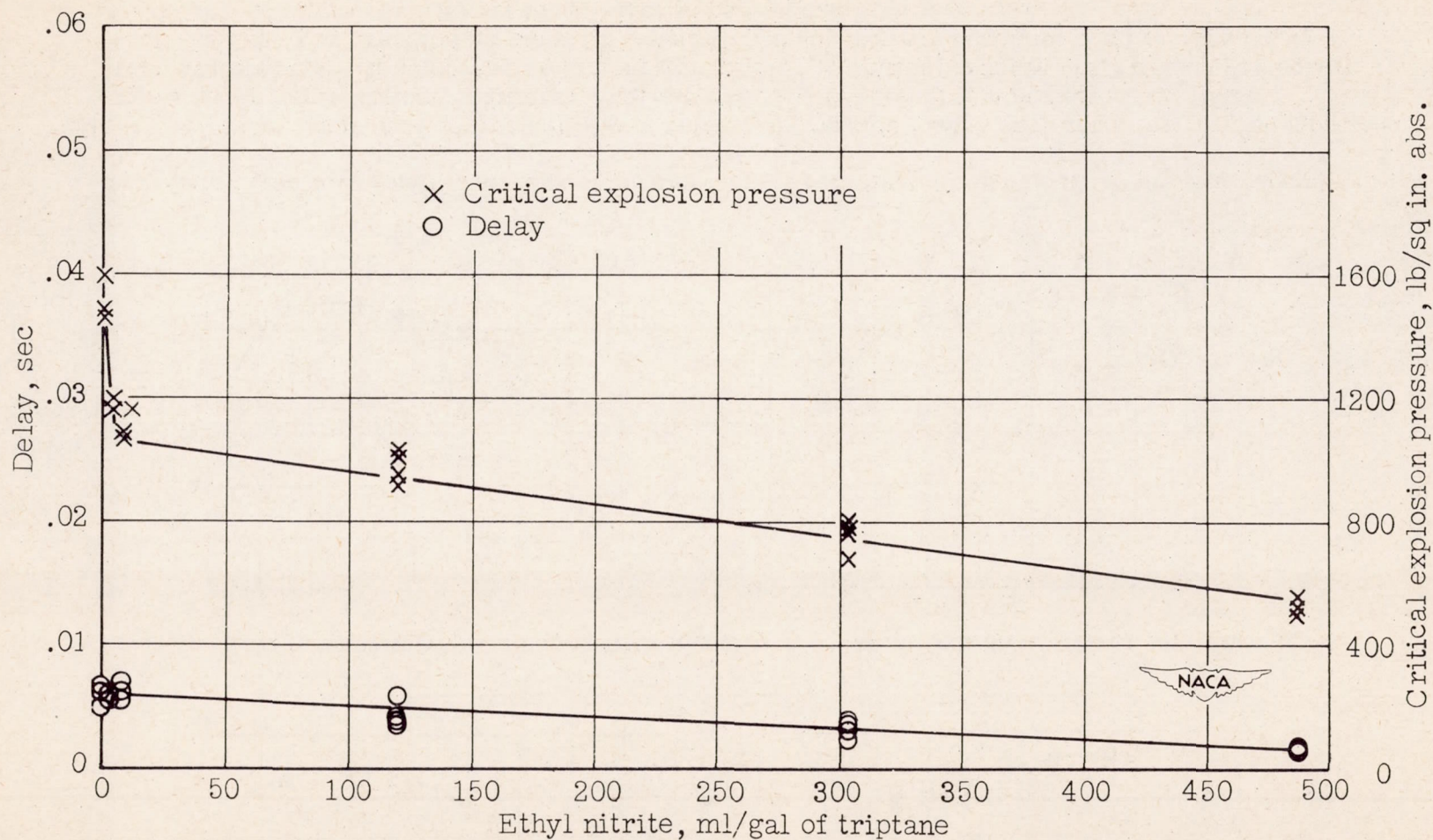
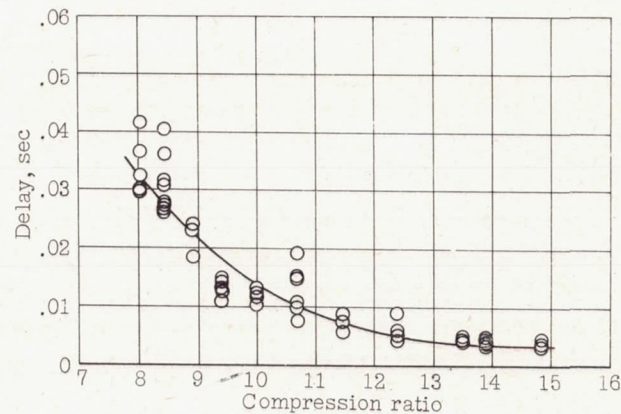
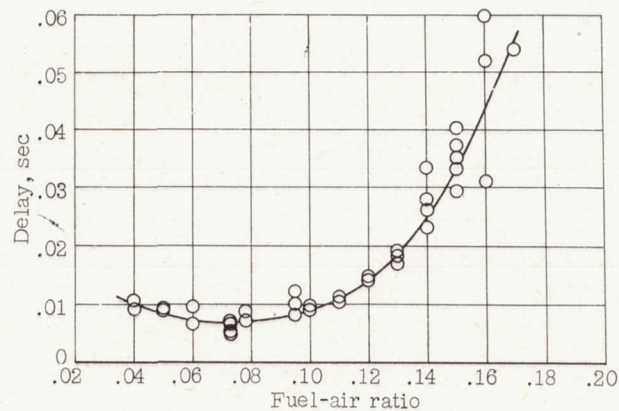
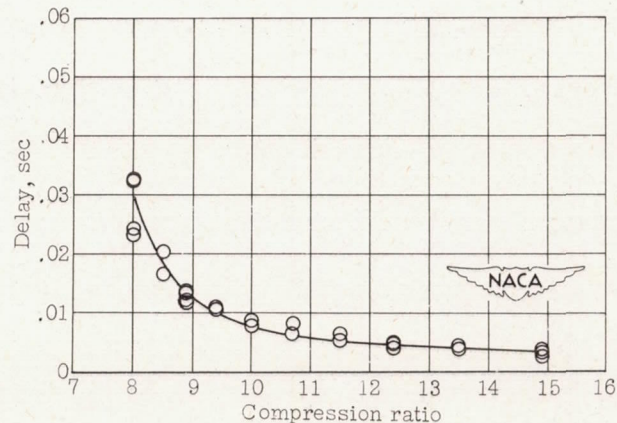
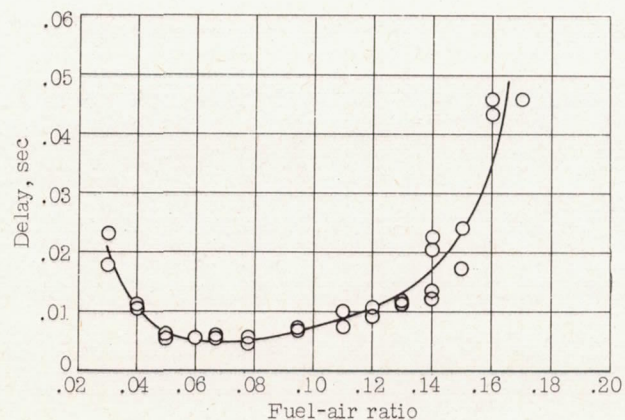


Figure 22.- Series 4 tests - the effect of ethyl nitrite on the ignition delay and critical explosion pressure of triptane. Fuel-air ratio, 0.066 (chemically correct); compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second; film speed, 200 inches per second.

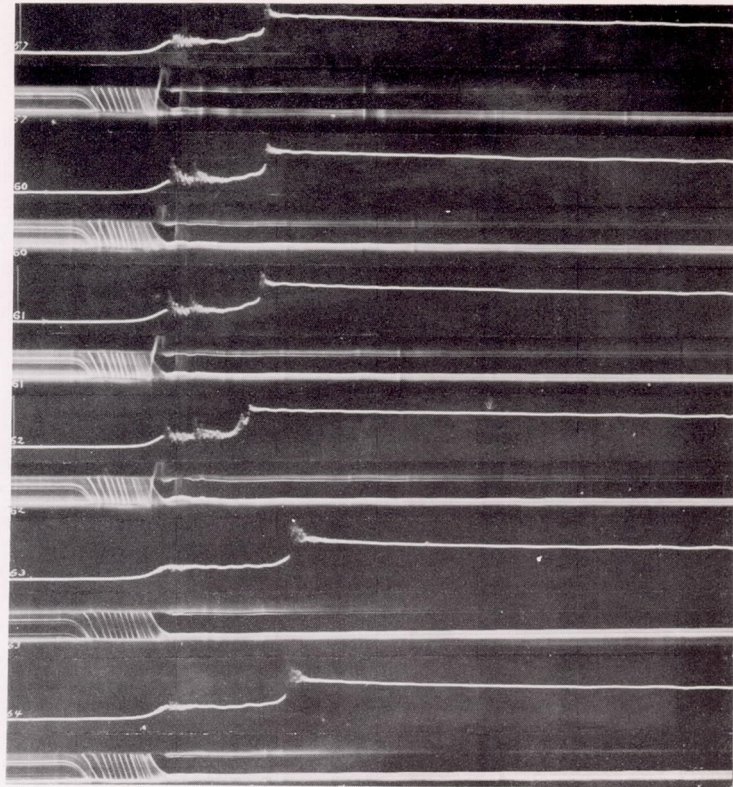


(a) Data taken with rapid compression machine 1. (From figs. 35 and 39 of reference 1.)

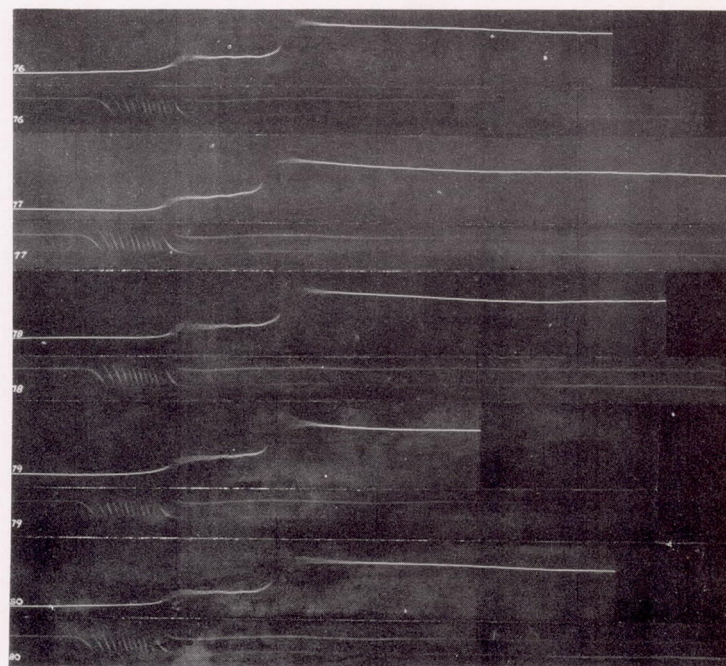


(b) Data taken with rapid compression machine 2. (From figs. 10 and 16 of the present paper.)

Figure 23.- Comparison of reproducibility of rapid compression machines 1 and 2 for runs on isooctane made under the following conditions: Fuel-air ratio, 0.067; compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second (approx.); film speed, 200 inches per second.



(a) Rapid compression machine 1.



0.005 sec

(b) Rapid compression machine 2.



Figure 24.- Explosion records for isooctane-air mixtures obtained with rapid compression machines 1 and 2. Fuel-air ratio, 0.067; compression ratio, 11.7; initial temperature, 609° R; compression temperature, 1340° R; initial pressure, 14.7 pounds per square inch absolute; compression pressure, 379 pounds per square inch absolute; compression time, 0.006 second (approx.); film speed, 200 inches per second.

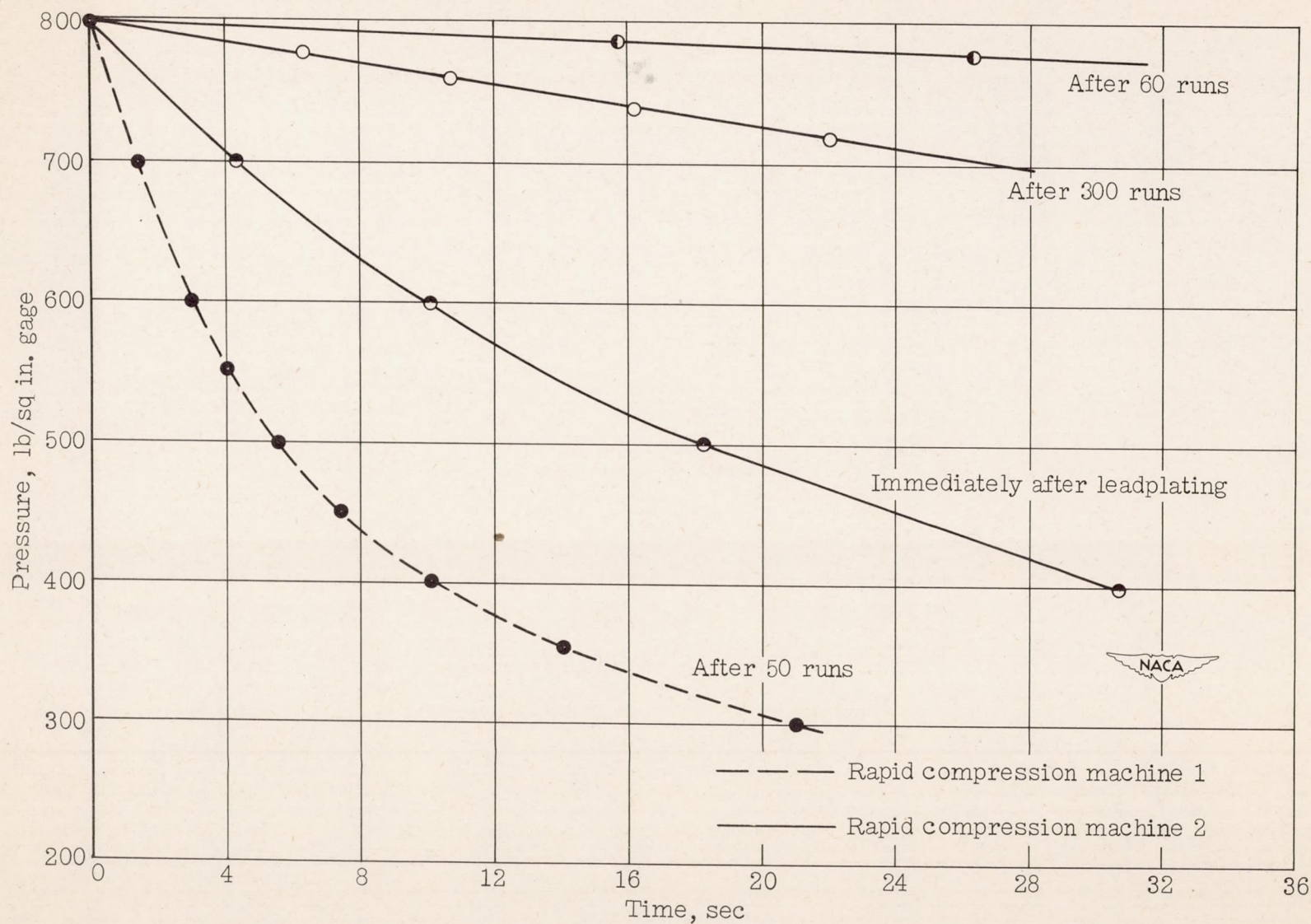


Figure 25.- Leakage curves - change in combustion-chamber pressure with time.